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PERFORMANCE RANKING OF FINNED TUBULAR HEAT EXCHANGER SURFACES

James Ernest Baskerville

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PERFORMANCE RANKING OF FINNED TUBULAR HEAT EXCHANGER SURFACES

by

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B.S., UNITED STATES NAVAL ACADEMY
Annapolis, Maryland
(1969)

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF OCEAN ENGINEER AND MASTER OF SCIENCE
IN MECHANICAL ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May 1977

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PERFORMANCE RANKING OF
FINNED TUBULAR HEAT EXCHANGER SURFACES

by

JAMES ERNEST BASKERVILLE

Submitted to the Department of Ocean Engineering on May 12, 1977 in partial fulfillment of the requirements for the degree of Ocean Engineer and Master of Science in Mechanical Engineering.

ABSTRACT

The traditional method of data presentation for heat exchanger surfaces does not permit comparison of individual surface types in any simple manner. This data is most commonly presented in terms of heat transfer coefficients and friction factors referenced to the exposed area as a function of Reynolds number based on the minimum free flow area.

Soland [5] proposed a method of surface comparison for plate-finned heat exchanger surfaces in which the heat transfer coefficient and friction factor is referenced to the base area and Reynolds number is based on the open flow area, as though the enhanced surfaces were not present.

Theory and principle inherent in the Soland proposal are used to develop a method of surface comparison for finned tube surfaces as presented in (a) Kays and London [2], and (b) several supplemental surfaces furnished by the Trane Corporation. The derived comparison method is evaluated by application to a practical crossflow finned tubular heat exchanger design.

Appendix III provides a method for sizing crossflow finned tubular heat exchangers.

Thesis Supervisor: Professor Warren M. Rohsenow
Title: Professor of Mechanical Engineering

ACKNOWLEDGEMENTS

To my wife and children, an expression of "Thank You" for three years of thoughtful, loving understanding.

To Professor Rohsenow, a sincere feeling of appreciation for suggesting this thesis topic and for the many hours of guidance helping me through the "uncharted waters".

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NOMENCLATURE

a_d	Minimum free flow dimension between tubes measured diagonally between adjacent rows from base to base as if fins were not present; see Figure 4, [FT]
a_t	Minimum free flow dimension between tubes measured transversely to the direction of flow from base to base as if fins were not present; see Figure 4, [FT]
A_b	Heat transfer area of the bare base tubular surfaces; equals length times heated perimeter times number of tubes; $[FT^2]$
A_c	Exchanger minimum free flow area, defined by (1a), $[FT^2]$
A_f	Constant from linearized equation for friction factor (f) of the form: $A\ RE^{B}$
A_F	Exchanger flow passage frontal area ignoring any enhancing surfaces; see Figure 4, $[FT^2]$
A_δ/A_T	Ratio of fin area to total transfer area, $[FT^2]$
A_{fr}	Exchanger total frontal area, $[FT^2]$
A_j	Constant from linearized equation for Colburn modulus (j) of the form: $A\ RE^{B}$
A_T	Total heat transfer area of exchanger on one side, defined by β times total volume, $[FT^2]$

b	Longitudinal center-to-center tube spacing, see Figure 4, [FT]
C	Flow stream capacity rate [WC_p], [BTU/HR-^{0}F]
C_D	Constant used in the computation of friction factor (f) for flow over smooth tube banks; defined by (32)
C_Δ	Constant required for the computation of radial fin efficiency; defined in Figure 5.
C_p	Specific heat at constant pressure, [BTU/LBM-^{0}F]
D_Δ	Constant required for the computation of radial fin efficiency; defined in Figure 5.
D_h	Hydraulic diameter, defined by (1a), [FT]
D_N	Nominal diameter, defined by (1b), [FT]
F	Transverse center-to-center tube spacing; see Figure 4, [FT]
f	friction factor based on total area (A_T); defined by (4a)
f_N	friction factor based on base area [A_b]; defined by (4b)
f_s	friction factor based on total area (A_T) for a smooth surface, defined by (31) or (32)
g_o	32.174 [LBM/LBF] [FT/SEC^2]

G_c	Mass flux based on minimum free flow area, [A_c], defined by (2a), [LBM/HR-FT^2]
G_N	Mass flux based on free flow area, [A_F], defined by (2b), [LBM/HR-FT^2]
h	Heat transfer coefficient based on total area, [A_T] defined by (5a), [BTU/HR-FT^2-°F]
h_N	Heat transfer coefficient based on base area, [A_b]; defined by (5b), [BTU/HR-FT^2-°F]
j	Colburn j-factor based on total area, [A_T]; defined by (7a)
j_N	Colburn j-factor based on base area, [A_b]; defined by (7b)
j_s	Colburn j-factor based on total area, [A_T], for a smooth surface, defined by (28)
K	Thermal conductivity [BTU/HR-FT-°F]
ℓ	Fin height defined by r_e-r_o; for rectangular fin sheets, see Figure 5, [FT]
L	Flow length along the axis of the tubes (i.e. for the fluid inside the tubes); for fluid flowing normal to the tube banks, defined as N times b; [FT]
m	Component of fin efficiency (η_{f-L}); defined by [10]
N	Number of tubes

N_R	Symbol used in reference [2] for RE
Nu	Nusselt number; defined by (6a)
Nu_N	Nusselt number; defined by (6b)
NTU	Number of transfer units; defined by (21)
$\eta_{\delta-L}$	Fin temperature effectiveness of a longitudinal fin of rectangular profile; defined by (9)
$\Delta\eta_{corr}$	Correction factor applied to $\eta_{\delta-L}$ (9) to permit the use of the simplier $[\text{Tanh } m\ell]/m\ell$ equation for fin temperature effectiveness in lieu of Bessel Function type equations.
η_o	Total surface temperature effectiveness, defined by (8)
Pr	Prandtl Number $[\mu C_p/K]$
P	Pressure $[LBF/FT^2]$
P	Pumping Power [HP]
ΔP_f	Friction pressure drop $[LBF/FT^2]$
q	Heat transfer rate [BTU/HR]
q/A	Heat Flux $[BTU/HR\text{-}FT^2]$
RE	Reynolds number based on minimum free flow area, $[A_c]$, defined by (3a), Labeled N_R by ref [2]

RE_N	Reynolds number based on free flow area, [A_F], defined by (3b)
r_e	Radius of enhanced (finned) surface, [FT]
r_o	Outside radius of base tube, [FT]
r_h	Hydraulic radius, equals hydraulic diameter divided by four for a round tube, [FT]
T	Temperature, [^{0}F]
U	Overall heat transfer coefficient [BTU/HR-FT^2-^{0}F]
V	Volume [FT^3]
W	Mass flow rate, [LBM/HR]
X,Y,Z	Principle dimensions of heat exchanger, [FT]
X_D	Ratio of diagonal tube spacing to tube outside diameter
X_L	Ratio of longitudinal tube spacing to tube outside diameter, equals b divided by D_o
X_T	Ratio of transverse tube spacing to tube outside diameter, equals F divided by D_o

Miscellaneous

α	In tube geometry, angle defined by the longitudinal centerline and the diagonal centerline; see Figure

	7, [degrees]
β	Ratio of total transfer area on one side of the exchanger to total volume of the exchanger, labeled as α in reference [2], $[FT^2/FT^3]$
Δ_1	-0.00259, Constant used to calculate C_Δ
Δ_2	-0.00840, Constant used to calculate C_Δ
Δ_3	-0.02426, Constant used to calculate D_Δ
Δ_4	-0.04521, Constant used to calculate D_Δ
δ	Fin thickness, or average fin thickness if tapered, [FT]
ε	Exchanger effectiveness
μ	Viscosity [LBM/HR-FT]
ρ	Density $[LBM/FT^3]$

Subscripts

d	diagonal
e	enhanced surface
m	heat exchanger fin material
0	outside

Subscripts (continued)

os	one side
s	smooth surface
t	transverse
T	Total
2	Finned side, colder fluid flowing over finned tube banks
1	Tube side; hotter fluid flowing inside smooth tubes

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I. INTRODUCTION

A. Purpose

The objective of any heat exchanger comparison method is to enable the designer to select, from an often overwhelming number of enhanced surfaces, that unique surface which can be termed "optimum". The comparison technique should be in the form of a logical, easily implemented, inherently accurate procedure.

It should be recognized from the onset that regardless of the definition of "optimum" selected, the surface labeled as such may not, in fact, be the best for a given practical situation. Space limitations or cost restraints frequently restrict the designers flexibility. While a particular surface may be "optimum" from a least volume criteria, for example, it may well exceed the cost limitations or require an unacceptably long dimension. Violation of either of these practical constraints could well force the selection of an alternate surface.

Soland [5] proposed a method of comparison that permits performance comparisons of all of the Kays and London [2] plate finned type heat exchanger surfaces on four different bases:

a. Same exchanger shape and volume

b. Same exchanger volume and pumping power

c. Same pumping power and NTU

d. Same volume and NTU

Sheldon [6], (a) applied Soland's method to practical heat exchanger design problems; (b) evalueated the method effectiveness; and (c) performed a comparative analysis on plate finned surfaces in addition to those found in Kays and London.

The purpose of this paper is to:

1. adapt Soland's method for application to crossflow finned tube type surfaces presented in (a) Kays and London; and, (b) several supplemental surfaces furnished by Trane Corporation;

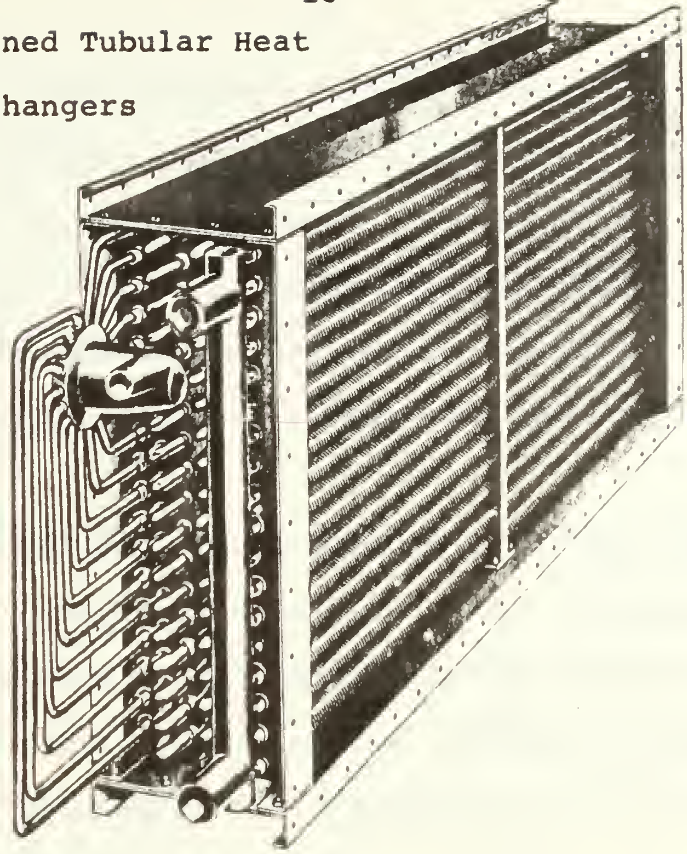
2. evaluate the method effectiveness by application to practical crossflow finned tubular heat exchanger design problems.

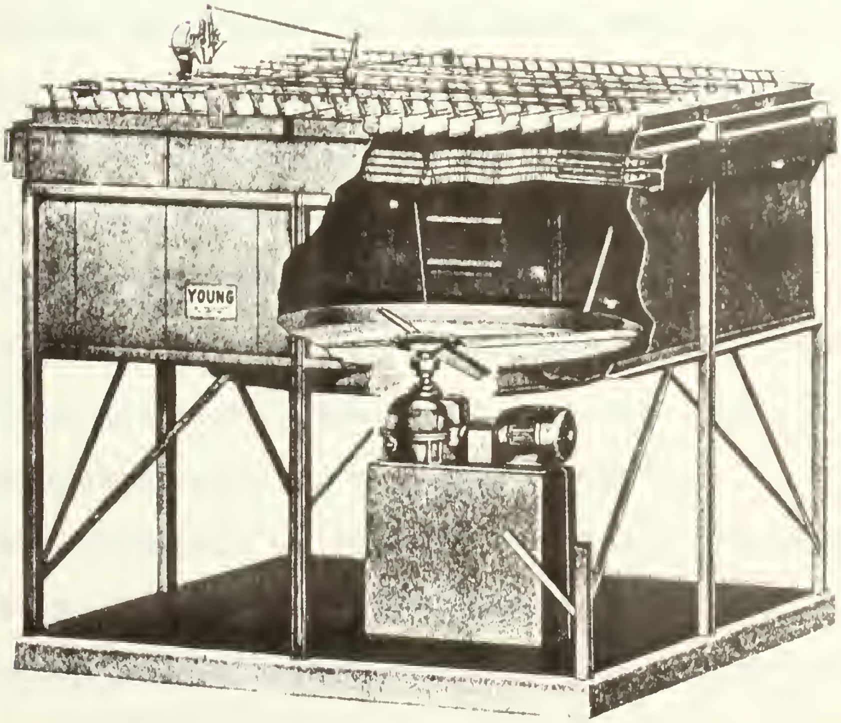
B. Background

Crossflow finned tubular heat exchangers have found application as gas turbine plant intercoolers, aircraft engine and electronics coolers, air conditioning units, heat exchangers, and numerous other uses. These applications most often involve gas-liquid service. [See Figure 1]

The performance of a given heat exchanger in which the ratio of the heat transfer coefficients between the two working fluids is greater than about three is markedly improved by the employemnt of enhanced surfaces. The increased surface area inherent with the employment of fins yields a net

FIGURE 1: Finned Tubular Heat Exchangers





improvement in heat transfer despite lower heat transfer coefficients. Finned tubular heat exchangers have surface-to-volume ratios (β) ranging between 20-200 ft^2/ft^3.

Reference [2] will be considered the primary source for data related to the design and testing of finned tubular surfaces, while supplemental data has been provided by the Trane Corporation.

Optimum design is often used synonomously with "lowest cost". Cost is frequently defined as (a) amortized acquisisition cost related to the initial design and fabrication of the component, (b) operating costs, defined as amortized acquisition cost plus operating expenses and (c) cost to the system in terms of either weight or volume.

Consider aircraft engine component design, for example, where weight and volume are valuable quantities which can be directly equated to dollar cost. An unnecessarily large support component impacts either payload or endurance.

It is certainly conceivable that a heat exchanger could be designed with (a) the least acquisition cost, (b) the lowest projected operating expenses, and yet (c) have the highest weight or volume impact on the parent design and therefore by unacceptable to to "impact cost".

The estimation of dollar cost of a particular heat exchanger design is difficult to estimate, primarily due to the proprietary nature of the required cost estimating relations.

Companies that design and manufacture heat exchangers are often quite reluctant to release this data.

A method of dollar cost comparison will be proposed, but due to lack of data, will not be fully investigated.

The term "cost", therefore, as used in this paper, will most generally refer to "impact cost" and will serve as a means of relative ranking of proposed designs specifically by required volume, pumping power and NTU comparison.

C. Surface Testing and Data Presentation

In order to provide the required friction and heat transfer data for a specified finned tubular surface, experimental testing is required.

The experimental procedure employed by Kays and London is clearly outlined in reference [2].

Regardless of the technique, the results include fanning friction factor f, Prandtl number, Reynolds number, and Colburn j-factor. Figure 2 is an example showing the traditional method of data presentation.

D. The Task of the Designer

Assuming that the designer of a heat exchanger has defined such constraints as:

(a) allowable pressure loss,

(b) temperature change,

(c) amount of heat to be transferred,

FIGURE 2: Sample data plot showing traditional method of data Presentation

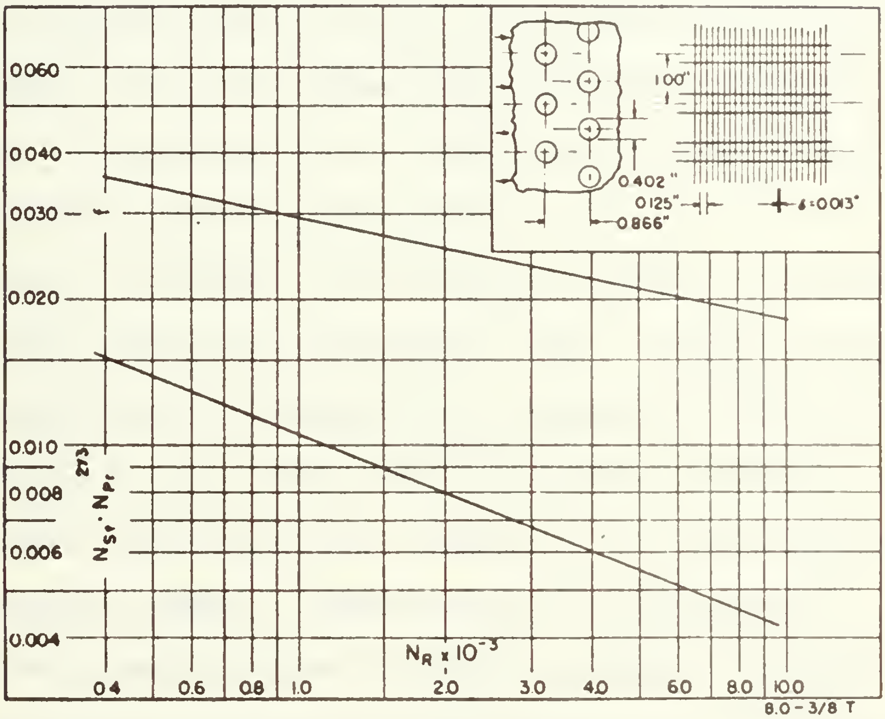


FIG. 100

FINNED CIRCULAR TUBES
SURFACE 8.0 - 3/8 T
(Data of Trane Co.)

Tube outside diameter - 0.402 in.
Fin pitch - 8.0 per inch
Flow passage hydraulic diameter - $4r_h$=0.01192 ft.
Fin thickness - 0.013 in.
Free-flow area/frontal area - σ =0.534
Heat transfer area/total volume - α =179 $ft.^2/ft.^3$
Fin area/total area - 0.830

Note: Minimum free-flow area in spaces transverse to flow.
These data are included in this compilation because they apply to a compact surface configuration of considerable technical interest for which no data have been obtained on this project.

(d) volume and weight restrictions,

(e) fouling and corrosion considerations

(f) materials

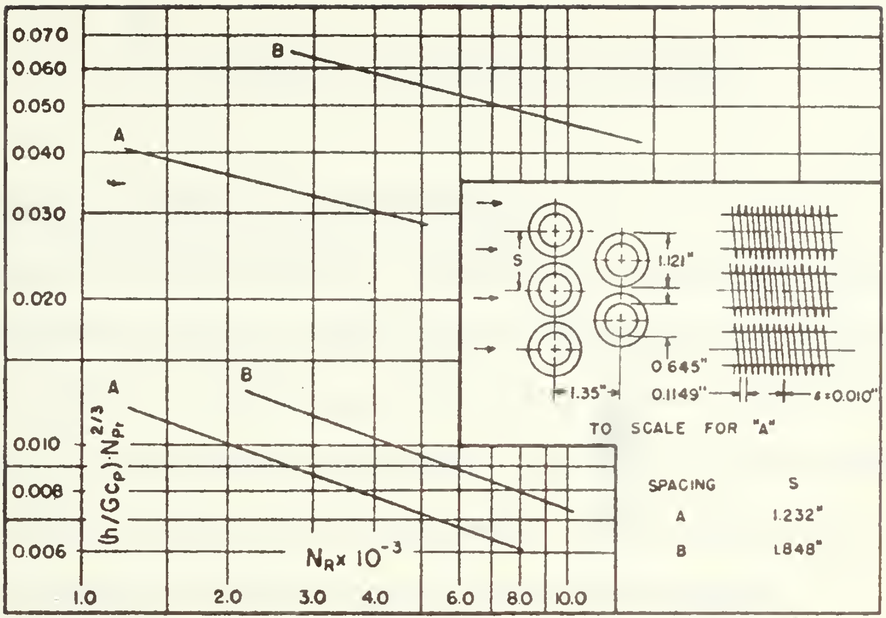
he is now ready to select the heat transfer surface(s) to be employed.

Having compiled a great number of candidate surfaces from (a) existing data, or (b) having designed and tested his own surface, he is now faced with the task of comparing these surfaces to determine which should be selected for the specific application under consideration.

Figure 3 presents two examples from Ref [2] showing the traditional method of presenting f and j verses RE data . Note that in each case, Surface B has a superior heat transfer characteristic at a given Reynolds number; however, Surface A has a lower (and therefore, superior) friction factor at that same Reynolds number. Which surface is "optimum"?

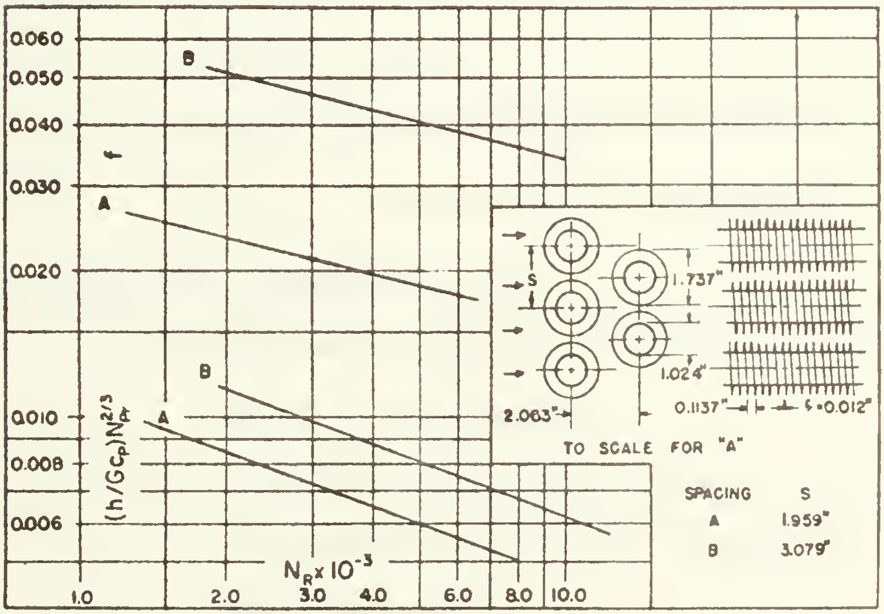
There appears to be no obvious answer to this question and this fact has prompted several methods of surface comparison to be developed.

It is intended that the method presented herein will provide a solution to this dilemma.



CF-8.7-5/8 J

Surfaces of Ref [2] Figure 97



CF 8.8 - 1.0 J

Surfaces of Ref [2] Figure 99

FIGURE 3: Two examples from REF [2] showing the traditional method of presenting f and j verses RE surface data, and showing the difficulty in comparing surfaces A and B in each case.

II. PROPOSED COMPARISON TECHNIQUE

A. Derivation of Basis of Comparison

Soland, in reference [5], provides a detailed derivation of the proposed surface comparison technique used to analyze the performance of crossflow plate-finned heat exchangers.

Theory and principle inherent with the Soland method are used to derive a comparison technique to analyze the performance of crossflow finned tubular heat exchangers.

Comparison of the performance of various finned tubular surfaces assumes the following quantities are held constant:

A) W, flow rate

B) $T_{h,in}$, hot fluid inlet temperature

C) $T_{c,in}$, cold gas inlet temperature

Other important assumptions are:

E) The heat transfer resistance of the tube walls is negligible.

F) The controlling heat transfer resistance is assumed to be on the finned side of the heat exchanger.

Traditionally, data is presented in terms of heat transfer Colburn modulus, j, and friction factor, f, based on the total exposed area, A_T, as a function of Reynolds number, RE, based on minimum free flow area, A_c, and a hydraullic diameter,

D_h, of the flow passage.

The proposed comparison method converts these j and f magnitudes to new quantities j_N and f_N based on the heat transfer area of the bare base tube surface, A_b, and a Reynolds number, RE_N, which is referenced to the open flow passage area, A_F, as though the fins were not present. The effect of the fins is accounted for as an increased heat flux and hence larger h for for the bare base tube surface area. In order to incorporate the effect of the fins into j_N, the metal conductivity must be specified.

Table I shows the proposed new definitions and compares them with the analogous definition used by Kays and London [2]. Two cases must be considered as illustrated in Figure 4.

In order to convert data presented in the format of reference [2] to the new basis, various ratios are derived from basic definitions, equations (1) through (10), and Figure 4. These ratios are presented in Table II.

Two assumptions and an explanation of the calculation of radial fin efficiency are required in order to solve for the proper fin efficiency, η_δ, needed in the conversion relations:

1. The results presented herein will assume the gas flowing over the finned tube banks is air whose thermodynamic properties will be evaluated at 90°F.
2. Some of the results presented herein specify copper fins [K≈222 BTU/HR-FT-°F] and others specify Aluminum fins [K≈117.6 BTU/HR-FT-°F].

TABLE I. DEFINITIONS

QUANTITY	KAYS AND LONDON [2]		PROPOSED	
Hydraulic Diameter	$D_h \equiv \frac{4\ A_c\ bN}{A_T}$	(1a)	$D_N \equiv \frac{4\ A_F\ bN}{A_b}$	(1b)
Mass Velocity	$G_c \equiv \frac{W}{A_c}$	(2a)	$G_N \equiv \frac{W}{A_F}$	(2b)
Reynolds Number	$N_R \equiv \frac{G_c\ D_h}{\mu}$	(3a)	$RE_N \equiv \frac{G_N\ D_N}{\mu}$	(3b)
Friction Factor	$f \equiv \frac{\Delta P_f}{4\ \frac{bN}{D_h}\ \frac{G_c^2}{2\rho g_o}}$	(4a)	$f_N \equiv \frac{\Delta P_f}{4\ \frac{bN}{D_N}\ \frac{G_N^2}{2\rho g_o}}$	(4b)
Heat Transfer Coefficient	$h \equiv \frac{[q/\eta_o]A_T}{\Delta T}$	(5a)	$h_N \equiv \frac{[q/A_b]}{\Delta T}$	(5b)
Nusselt Number	$Nu \equiv \frac{D_h\ h}{k}$	(6a)	$Nu_N \equiv \frac{D_N\ h_N}{k}$	(6b)

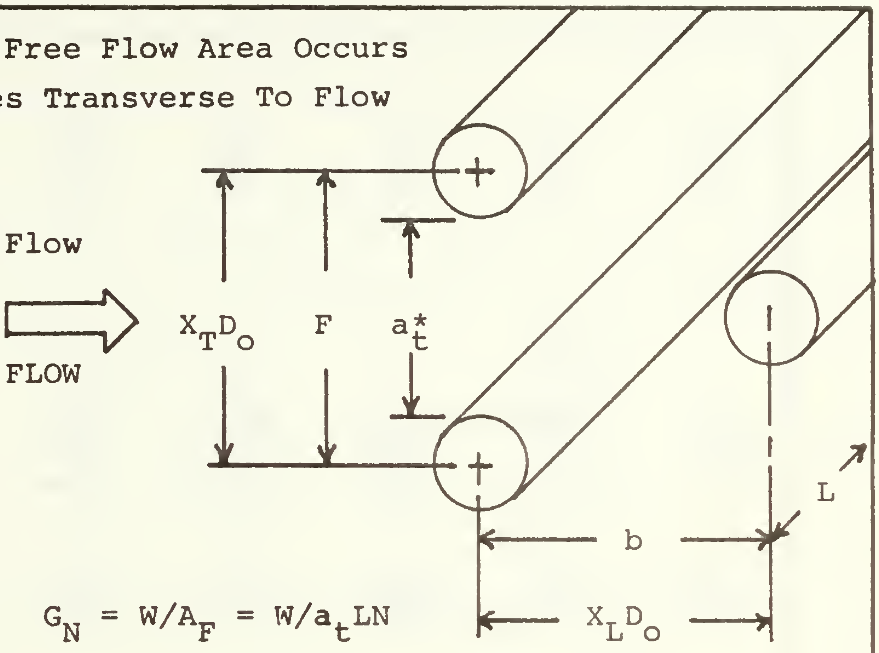
TABLE I. DEFINITIONS (continued)

QUANTITY	KAYS AND LONDON [2]		PROPOSED	
Colburn j	$j \equiv \frac{h}{G_c \; C_p} (Pr)^{2/3}$	(7a)	$j \equiv \frac{h_N}{G_N \; C_p} (Pr)^{2/3}$	(7b)
	$\eta_o \equiv 1 - \frac{A_\ell}{A_T}[1-\eta_\ell]$	(8)		
	$\eta_{\ell-L} \equiv \frac{\text{Tanh } m\ell}{m\ell}$	(9)**		
	$m \equiv \sqrt{(2h)/\delta \; k_m}$	(10)		

** Use of this formula for computing fin efficiency of a radial fin is permitted as outlined in Figure 5

CASE I: Minimum Free Flow Area Occurs In Spaces Transverse To Flow

*Minimum Free Flow Dimension



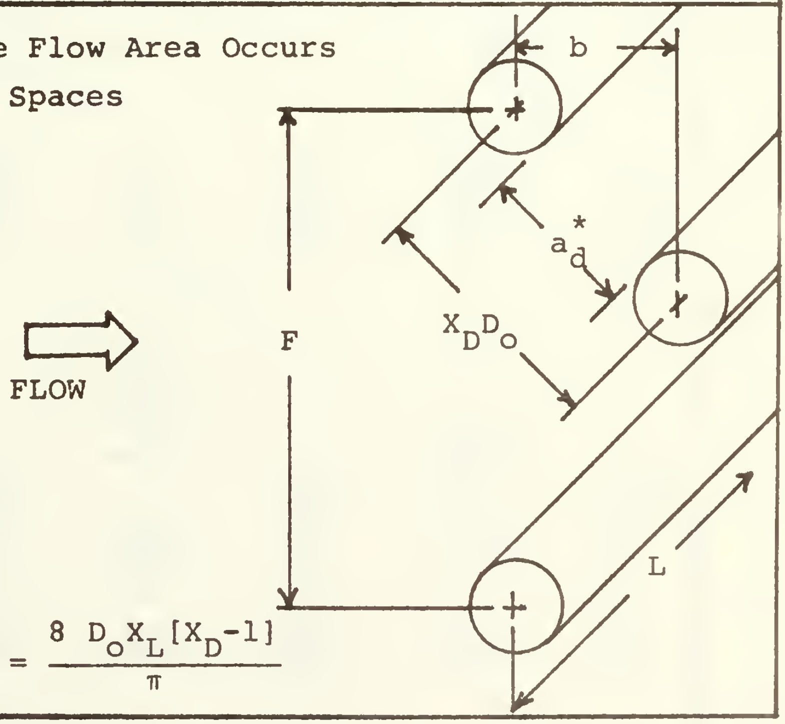
$A_F = a_t LN$

$A_b = \pi D_o LN$ $\qquad G_N = W/A_F = W/a_t LN$

$V_T = FbLN$ $\qquad D_N = \frac{4\ A_F b}{A_b} = \frac{4\ a_t b}{\pi\ D_o} = \frac{4\ D_o X_L [X_T - 1]}{\pi}$

CASE II: Minimum Free Flow Area Occurs In Diagonal Spaces

*Minimum Free Flow Dimension



$A_F = 2\ a_d LN$

$A_b = \pi D_o LN$

$V_T = FbLN$

$D_N = \frac{4\ A_F b}{A_b} = \frac{8\ a_d b}{\pi D_o} = \frac{8\ D_o X_L [X_D - 1]}{\pi}$

FIGURE 4: The Two Cases of Minimum Free Flow Area Occurance and the Associated Geometric Relations of Each Case.

[illegible]

[illegible]

TABLE II: Derived Ratios used to Convert Data Found in the Literature to the New Basis

CASE I		CASE II	
$\frac{A_b}{A_T} = \frac{\pi D_o}{\beta b F}$	(11a)	$\frac{A_b}{A_T} = \frac{\pi D_o}{\beta b F}$	(11b)
$\frac{A_F}{A_c} = \frac{4 a_t}{\beta F D_h}$	(12a)	$\frac{A_F}{A_c} = \frac{8 a_d}{\beta F D_h}$	(12b)
$\frac{G_N}{G_c} = \frac{A_c}{A_F} = \frac{\beta F D_h}{4 a_t}$	(13a)	$\frac{G_N}{G_c} = \frac{\beta F D_h}{8 a_d}$	(13b)
$\frac{RE_N}{N_R} = \frac{\beta b F}{\pi D_o}$	(14a)	$\frac{RE_N}{N_R} = \frac{\beta b F}{\pi D_o}$	(14b)
$\frac{f_N}{f} = \frac{16 a_t^2 D_N}{\beta^2 F^2 D_h^3}$	(15a)	$\frac{f_N}{f} = \frac{64 a_d^2 D_N}{\beta^2 F^2 D_h^3}$	(15b)
$\frac{j_N}{j} = \frac{\eta_o D_N}{D_h}$	(16a)	$\frac{j_N}{j} = \frac{\eta_o D_N}{D_h}$	(16b)

3. Figure 5 explains a proposed generalized procedure for estimating radial fin efficiency. This procedure provides a simplifed method of efficiency calculation in lieu of using more technically correct Bessel function type relations.

Figure 6 shows an example of data presented on both basis. It should be noted that additional curves of j_N verses RE_N would result for other magnitudes of fin thermal conductivity.

For any heat exchanger, the fluid pumping power per unit volume on one side is given by:

$$\frac{P}{V_{os}} = \frac{W \ \Delta P_f}{\rho \ V_{os}} \tag{17}$$

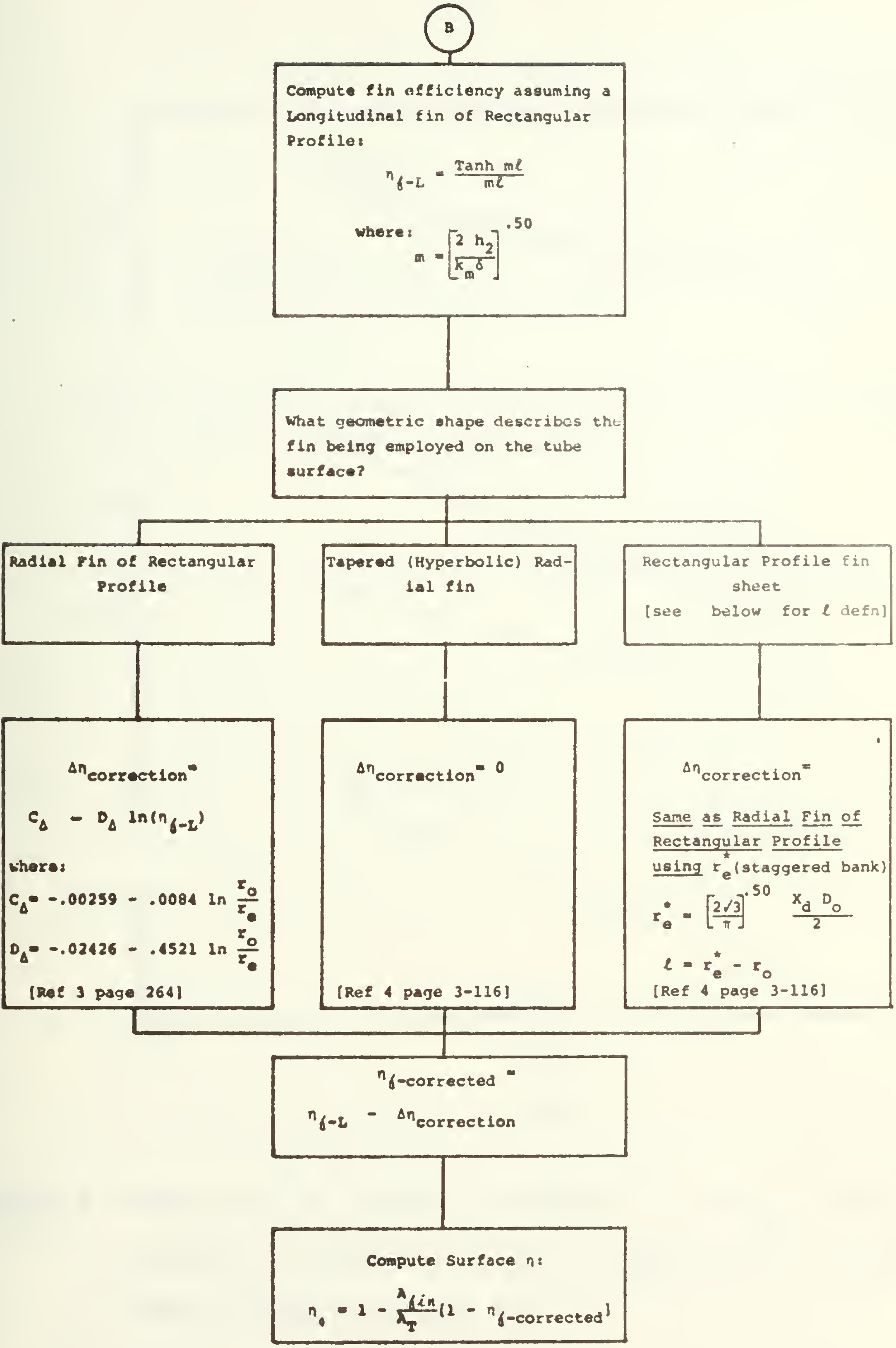
From equation 4b:

$$\Delta P_f = \frac{f_N \ 4 \ N \ b \ G_N^2}{D_N \ 2 \ \rho \ g_o}$$

From equation 2b:

$$W = G_N \ A_F$$

$$\frac{P}{V_{os}} = \frac{2 \ \mu^3 \ f_N \ RE_N^3 \ A_F \ b}{g_o \ \rho^2 \quad D_N^4 \ V_{os}} \tag{18}$$



Compute fin efficiency assuming a Longitudinal fin of Rectangular Profile:

$$\eta_{f-L} = \frac{\text{Tanh } m\ell}{m\ell}$$

where:

$$m = \left[\frac{2\ h_2}{k_m \delta}\right]^{.50}$$

What geometric shape describes the fin being employed on the tube surface?

Radial Fin of Rectangular Profile

$$\Delta\eta_{correction} = C_\Delta - D_\Delta \ln(\eta_{f-L})$$

where:

$$C_\Delta = -.00259 - .0084 \ln \frac{r_o}{r_e}$$

$$D_\Delta = -.02426 - .4521 \ln \frac{r_o}{r_e}$$

[Ref 3 page 264]

Tapered (Hyperbolic) Radial fin

$$\Delta\eta_{correction} = 0$$

[Ref 4 page 3-116]

Rectangular Profile fin sheet [see below for ℓ defn]

$\Delta\eta_{correction} =$

Same as Radial Fin of Rectangular Profile using r_e^* (staggered bank)

$$r_e^* = \left[\frac{2\sqrt{3}}{\pi}\right]^{.50} \frac{X_d\ D_o}{2}$$

$$\ell = r_e^* - r_o$$

[Ref 4 page 3-116]

$$\eta_{f\text{-corrected}} = \eta_{f-L} - \Delta\eta_{correction}$$

Compute Surface η:

$$\eta_s = 1 - \frac{A_{fin}}{A_T}(1 - \eta_{f\text{-corrected}})$$

FIGURE 5: Computing fin efficiency of a Radial fin

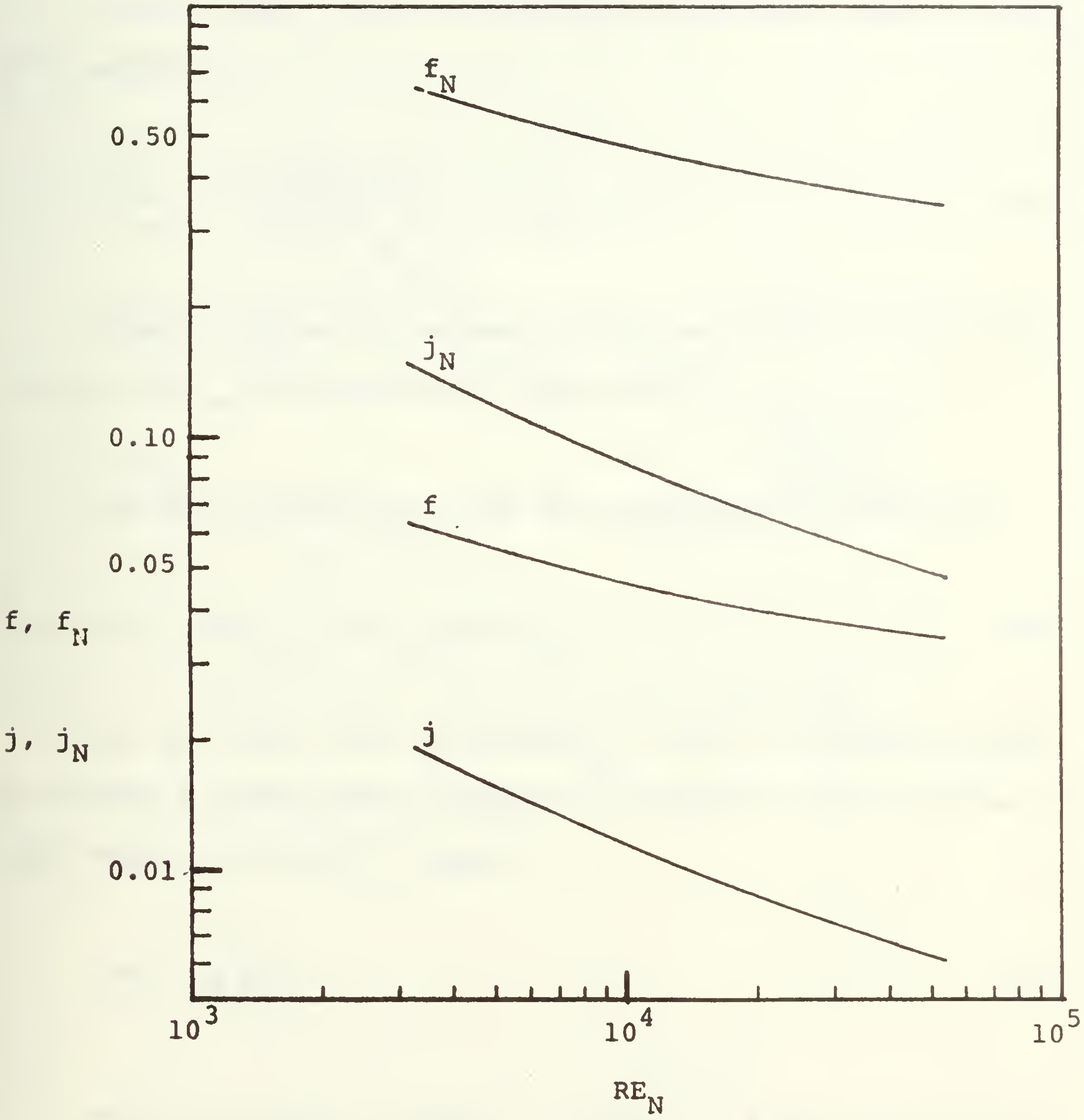


FIGURE 6: Comparison of Colburn j factors (j and j_N), and comparison of friction factors (f and f_N) for the Surface of Figure 94 [Ref 2].

[illegible]

For the same fluid at the same temperature level, μ and ρ are constant:

$$\frac{P}{V_{os}} \propto \frac{f_N \; RE_N^3 \; A_F \; b}{D_N^4 \; V_{os}} \tag{19}$$

Figure 7 shows the geometry involved in the calculation of $[A_F \; b]/V_{os}$ for both case I and case II.

The heat transfer for any heat exchanger is given by:

$$q = \varepsilon [T_{h,in} - T_{c,in}] W \; C_p \tag{20}$$

For any given flow arrangement, ε can be related to NTU by either a closed form equation or graphical curve similar to that shown in figure 8, where

$$\mathrm{NTU} \equiv \frac{A \; h_N}{W \; C_p} \tag{21}$$

The relationship between ε and NTU is always monotonically increasing. In other words, an increase in $A \; h_N$ causes an increase in NTU which means ε and hence q are greater, given that the fluid properties and flow rate are held constant.

From equations (21) and (7b):

Case I: Minimum Free flow area Transverse to Flow Direction

Total Volume on one Side:

$$V_{os} = [X_T D_o][X_L D_o]L - \frac{\pi}{4} D_o^2 L$$

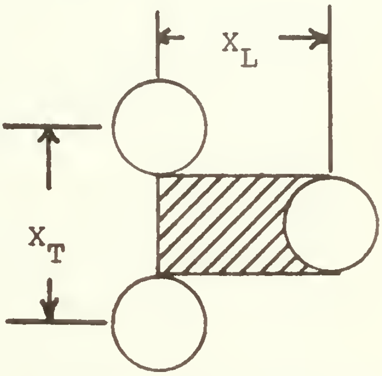
L = dimension into paper along flow length of tubes.

"A_F b" Volume: ▨

$$A_F b = [X_T D_o - D_o] L X_L D_o$$

Ratio:

$$\frac{A_F b}{V_{os}} = \frac{[X_T - 1] X_L}{X_T X_L - \pi/4}$$



Case II: Minimum Free Flow area in the Diagonals

Total Volume on one Side:

$$V_{os} = \frac{[D_o^2 X_D^2 \sin\alpha - \frac{\pi}{4} D_o^2]}{2}$$

"A_F b" Volume:

$$A_F b = 2 X_L D_o [X_D - 1] D_o$$

Ratio:

$$\frac{A_F b}{V_{os}} = \frac{4[X_D - 1] X_L}{X_D^2 \sin\alpha - \frac{\pi}{4}}$$

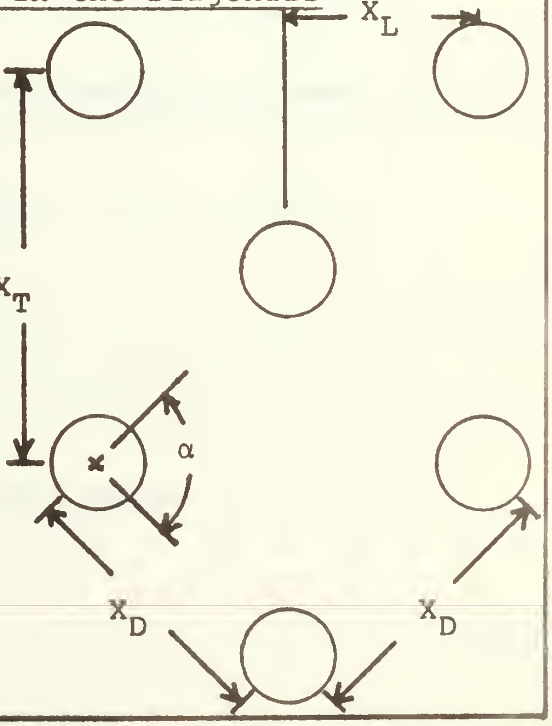


FIGURE 7: Calculation of $[A_F b]/V_{os}$ for both case I and II.

$$\frac{NTU}{V_{os}} = \frac{A_b\ h_N}{V_{os}\ W\ C_p} = \frac{A_b\ j_N\ G_N\ C_p}{P_r^{2\ 3}\ V_{os}\ W\ C_p} \qquad (22)$$

From equations (3b) and (1b):

$$\frac{NTU}{V_{os}} = \frac{4\ A_F\ b\ j_N\ RE_N\ \mu}{D_N^2\ P_r^{2\ 3}\ W\ V_{os}} \qquad (23)$$

or

$$\frac{A\ h_N}{V_{os}} = \frac{4\ C_p\ \mu}{P_r^{2\ 3}}\ \frac{j_N\ RE_N}{D_N^2}\ \frac{A_F\ b}{V_{os}} \qquad (24)$$

For the same fluid at the same temperature level, C_p, μ, and P_r are constant:

$$\frac{A\ h_N}{V_{os}} \propto \frac{j_N\ RE_N}{D_N^2}\ \frac{A_F\ b}{V_{os}} \qquad (25)$$

And for the flow rate, W, also constant:

$$\frac{NTU}{V_{os}} \propto \frac{j_N\ RE_N\ \ A_F\ b}{D_N^2\ \ \ V_{os}} \qquad (26)$$

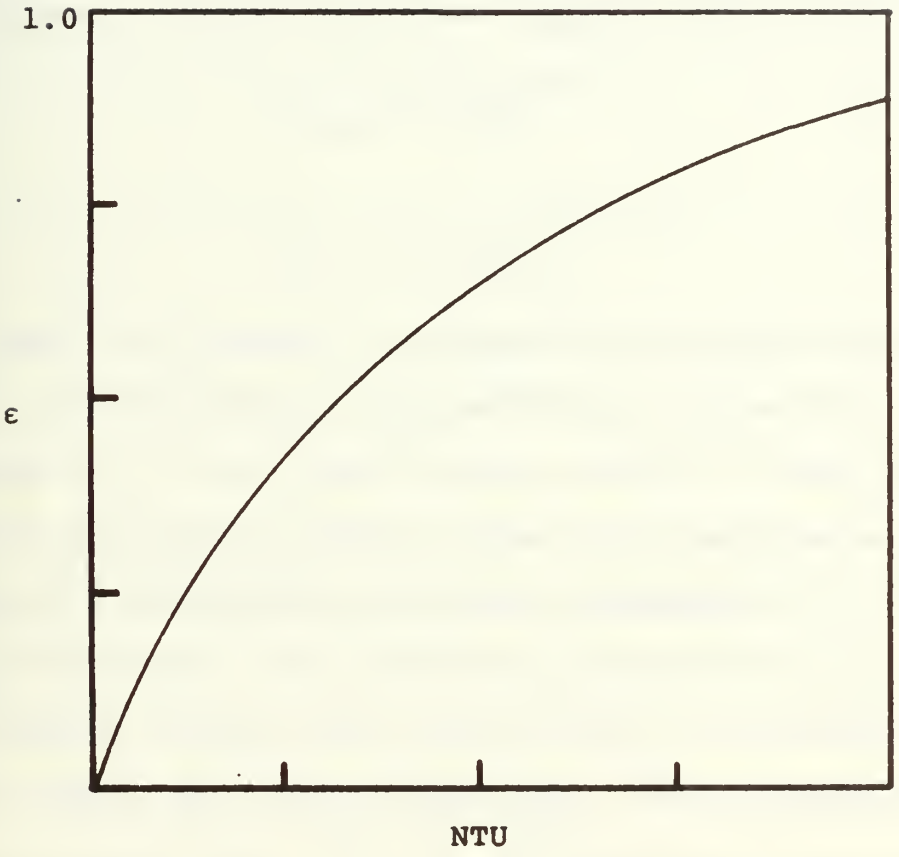


FIGURE 8: Typical Graphical Relationship between heat exchanger effectiveness and NTU. In general it is possible to express:

$$\varepsilon = \Phi[\mathrm{NTU},\ C_{min}/C_{max},\ \text{flow arrangement}]$$

[illegible]

Recognizing that the f and j verses RE plots for flow over finned tube banks from reference [2] can be closely approximated by a straight line on a log-log plot, implies that f and j can be represented by an equation of the form:

$$f_{(e)} = A_f \; RE^{B_f}$$

$$j_{(e)} = A_j \; RE^{B_j}$$

Table I of Appendix III lists the linearized equations of f and j for the surfaces represented by figures 92 -101 of reference [2]. This simplification allows for ease in programming the derived surface comparison equations as demonstrated in the procedure outlined in Appendix I.

In any event, the performance parameters may be calculated from enhanced surface data once the data is presented in the form f_N verses RE_N and j_N verses RE_N. This presentation may be (a) graphical due to the complex relations presented by f and j verses RE, as suggested by Soland or (b) analytical, as outlined in Appendix I, due in large part to the linear nature of f and j verses RE on a log-log plot.

B. Method of Surface Comparison

Having expressed the enhanced surface data in the form f_N verses RE_N and j_N verses RE_N, it is a relatively simple matter

to calculate the performance parameters of equations (19) and (26) and plot them. Figure 9 is an example of such a plot. The performance parameters of two hypothetical surfaces, labeled 1 and 2, have been plotted in order to demonstrate how a determination of heat exchanger relative performance may be made.

Four different comparisons are immediately available from figure 9 and are indicated by points a, b, c, and d on surface 2. Point o on surface 1 represents the reference heat exchanger design to which each of the four points on surface 2 will be compared.

Case A: Same heat exchanger shape and volume ($L_a=L_o$, $V_a=V_o$, $A_{F_a}=A_{F_o}$). Because W and A_F are fixed:

$$RE_{N_a} = RE_{N_o} \frac{[D_{N_a}]}{[D_{N_o}]} \qquad (27)$$

The results of this comparison are easily obtained as the ratios of ordinate values $[NTU/V_{os}]$ and abscissa values P/V_{os} of the two surfaces.

Case B: Same heat exchanger volume and pumping power ($V_b=V_o$, $P_b=P_o$). Point b is located on a vertical line through point o since the pumping power per unit volume is

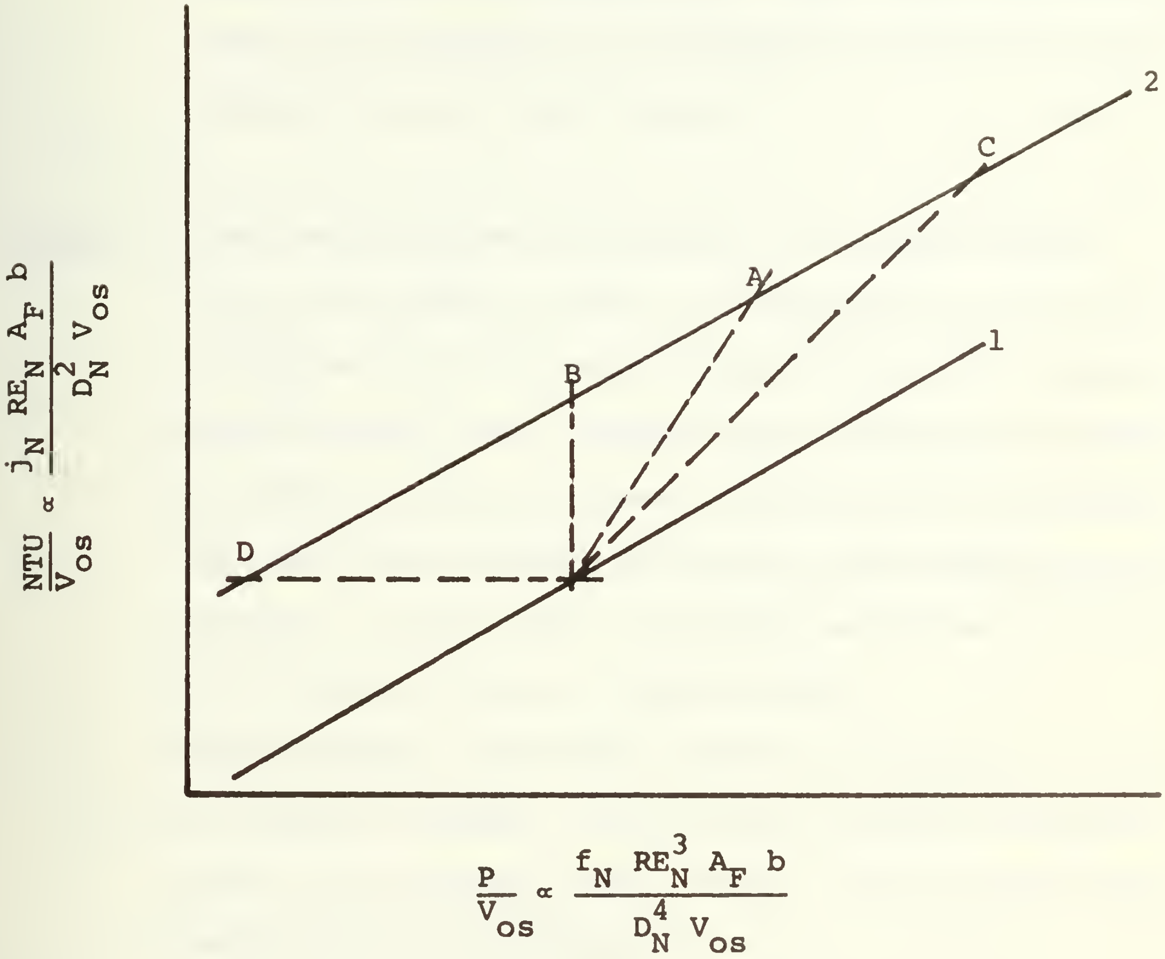

2
C
A
1
B
D
$\frac{NTU}{V_{os}} \propto \frac{j_N \; RE_N \; A_F \; b}{D_N^2 \; V_{os}}$
$\frac{P}{V_{os}} \propto \frac{f_N \; RE_N^3 \; A_F \; b}{D_N^4 \; V_{os}}$

FIGURE 9: Performance Parameter Curves For Two Hypothetical Surfaces Showing Points Used in Sample Comparisons.

Case B: (continued)

identical in both exchangers. The NTU ratio of the two heat exchangers is obtained as the ratio of the ordinate values from Figure 9.

Case C: Same pumping power and number of transfer units. ($P_c=P_o$, $NTU_c=NTU_o$) Point c is located on a line having slope equal to unity and through point o since both NTU and P are constant and each axis is inversely proportional to volume. The ratio of the volume required using surface 2 to the volume required using surface 1 is the ratio of either ordinates or abscissas at points o and c, respectively.

Since material costs are usually a function of volume or material weight, and thus heat transfer surface area, it is through Case C that a relative cost comparison may be attempted:

$$\frac{[\text{Total Cost}]_2}{[\text{Total Cost}]_1} = \frac{[\$/FT^2]_2\ [\beta]_2\ [V_T]_2}{[\$/FT^2]_1\ [\beta]_1\ [V_T]_1}$$

Note that as long as surface 2 lies above surface 1, the result will be a smaller volume required to do the same "job". [see Figure 9]

Case D: Same volume and number of transfer units. ($V_d=V_o$, $NTU_d=NTU_o$ or $q_d=q_o$). This case compares the pumping

Case D: (continued)

power required by surface 2 to that required by surface 1 for the case when both heat exchangers yield the same overall heat transfer performance. The comparison is made by taking the ratio of the abscissas (points o and d) in Figure 9, since a horizontal line on the performance plot has a constant value of NTU/V_{os}. The surface 2 Reynolds number for this case is the smallest of all four cases and consequently, the flow area is the largest. Since the volume is the same as the surface 1 exchanger, the length must decrease.

C. Summary

Using the equations derived herein it is possible to construct a performance parameter plot of NTU/V_{os} verses P/V_{os} (see Figure 9), from which it is possible to obtain useful performance comparisons between two heat exchangers for four different criteria.

III. COMPARISON OF FINNED TUBE SURFACES

A. General

Using the procedure derived in Chapter II and outlined in Appendix I, all the finned tube surfaces were plotted as performance curves of:

$$\frac{j_N \, RE_N \, A_F \, b}{D_N^2 \, V_{os}} \quad \text{verses} \quad \frac{f_N \, RE_N^3 \, A_F \, b}{D_N^4 \, V_{os}}$$

These performance curves assume constant W, $T_{c,in}$, and $T_{h,in}$, and are equivalent to NTU/V_{os} verses P/V_{os}.

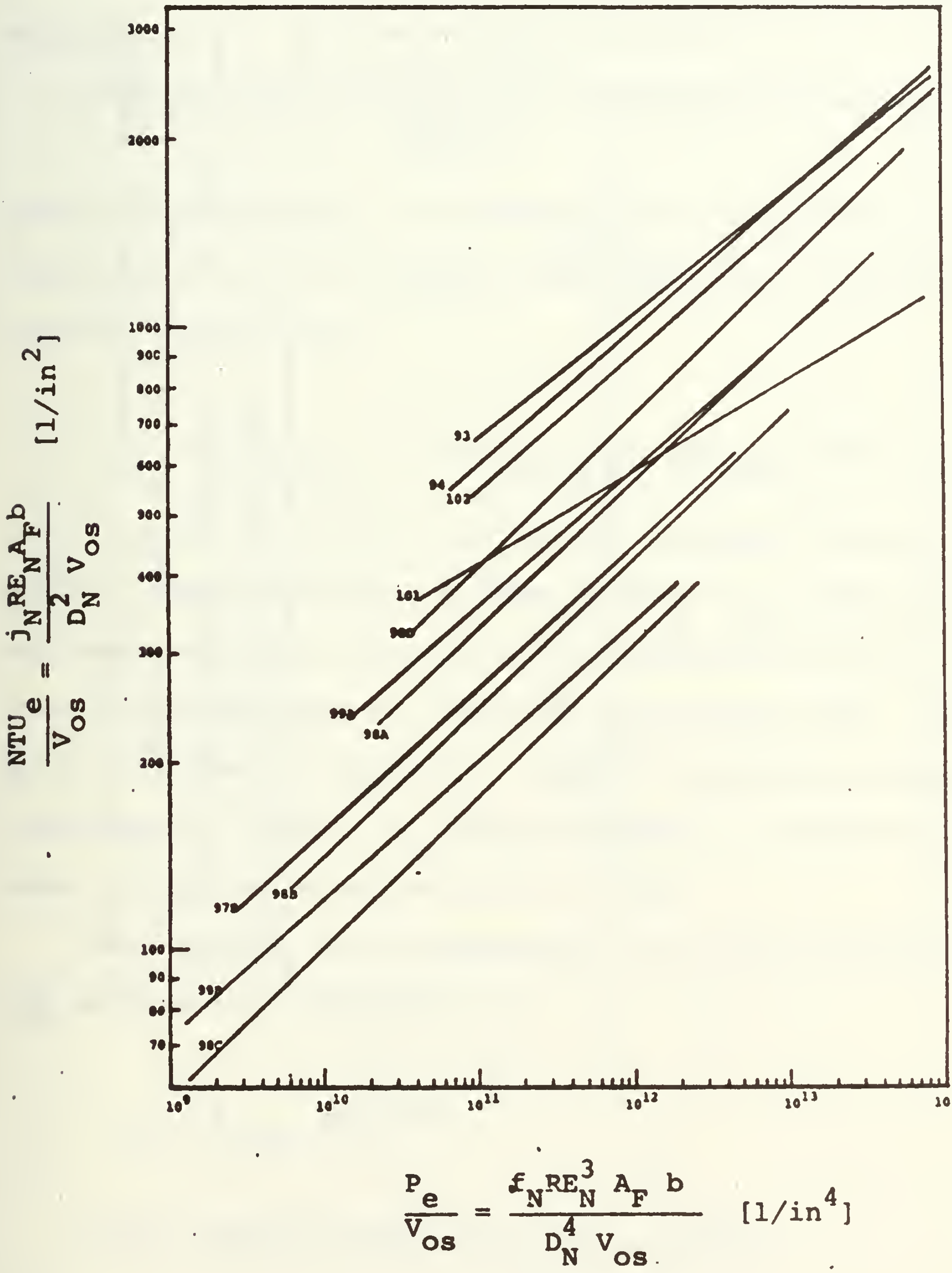
Figure 10 shows the resulting performance parameter plot presenting only the highest performance curve at each nominal diameter [D_N]. This study considered sixteen different surfaces having eleven different nominal diameters. Calculated performance results are presented for each surface considered in Appendix II.

B. Comparison to Smooth Surface

All of the sixteen finned tubular surfaces were then compared to a smooth surface having no enhancements (fins) and a nominal diameter identical to that of the enhanced surface.

PERFORMANCE PARAMETER CURVE FOR FINNED TUBULAR SURFACES

FIGURE 10



Note that subscript e will be used to denote the enhanced surface and the subscript s will be used to denote the smooth surface.

Smooth surface $\frac{j_s \ RE_N \ A_F \ b}{D_N^2 \ V_{os}}$ calculations were completed using the Zhukauskas [7] correlation for forced-convection, turbulent flow over staggered tube banks with the appropriate nominal diameter $[D_N]$.

$$j_s = 0.35 \ [RE]^{-0.396} \ [X_T/X_L]^{1/6} \ [D_o/D_N]^{-0.400} \qquad (28)$$

In order to justify the use of the above relation to predict smooth tube bank Colburn Modulus $[j_s]$, equation (28) was used to predict the actual heat transfer data for flow over bare tube banks as presented in reference [2]. The results are shown in figure 11. Maximum deviation between the experimental value of j_s (from reference 2) and the calculated value of j_s from equation (28) is ±7.5%.

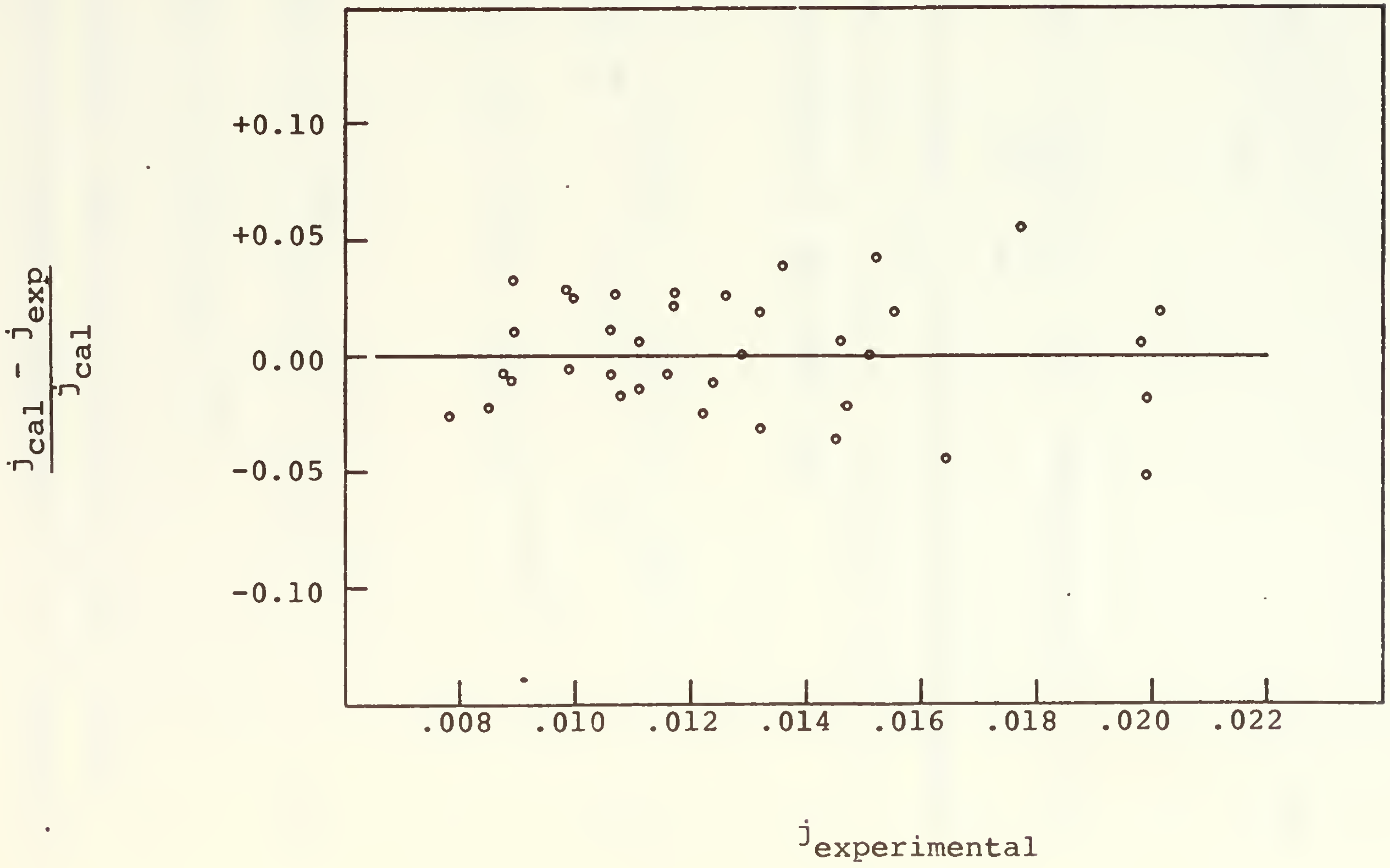
Note that j_s may be presented for each individual enhanced surface, in the form:

$$j_s = A_{j(s)} \ RE_N^{\ B_{j(s)}} \qquad (29)$$

For a smooth surface $h=h_N$, $G=G_N$, $RE=RE_N$

FIGURE 11

Deviation of the Zhukauskas [7] correlation for forced-convection, turbulent flow over staggered tube banks in predicting experimentally obtained value of Colburn modulus [j_s] as presented in reference [2].



Equation (26) may then be written for the enhanced surface as "if smooth":

$$\frac{NTU_s}{V_{os}} = \frac{j_{(s)}\ RE_N\ A_F\ b}{D_N^2\ \ V_{os}} \tag{30}$$

Smooth surface $\frac{f_s\ RE_N^3\ A_F\ b}{D_N^4\ \ V_{os}}$ were completed using a correlation for friction factor (f_s) derived from first principles using the Kays and London [2] data for turbulent flow over staggered bare tube banks as the data base:

Case I:

$$f_s = 0.7184\ RE^{-0.2407}\ [X_T-1]^{0.703}\ [X_L]^{C_T} \tag{31}$$

where: $C_T = 0.828 - 16.596\ RE^{-0.4277}$

Case II:

$$f_s = 1.0000\ RE^{-0.1892}\ [X_D-1]^{0.703}\ [X_L]^{C_D} \tag{32}$$

where: $C_D = 130.10\ RE^{-0.7284}$

Reference to Case I and Case II differentiates between minimum free flow area occuring transversely (I) or diagonally

(II) to the flow direction. (see Figure 4).

In order to justify the use of equations (31) and (32) to predict smooth tube bank friction factor (f_s), these relations were used to predict the actual experimental friction factor data for flow over bare tube banks as presented in reference [2]. The results are shown in Figure 12. Maximum deviation between the experimental value of f_s (from reference 2) and the calculated value from either (31) or (32) is ≈3.0%.

The friction factor, for each individual enhanced surface may be presented in the form:

$$f_s = A_{f(s)} \; RE_N^{B_{f(s)}} \tag{33}$$

Equation (19) may then be written for the enhanced surface as "if smooth":

$$\frac{P}{V_{os}} = \frac{f_s \; RE_N^3 \; A_F \; b}{D_N^4 \; V_{os}} \tag{34}$$

Of the sixteen surfaces investigated, five have a nominal diameter $[D_N] \approx 1.60$ inches. Since this offers an excellent means of comparison, cases A,B,C, and D where calculated for these five surfaces:

FIGURE 12

Deviation of the derived correlation for forced-convection, turbulent flow over staggered tube banks in predicting experimentally obtained value of friction factor [f_s] as presented in Ref [2].

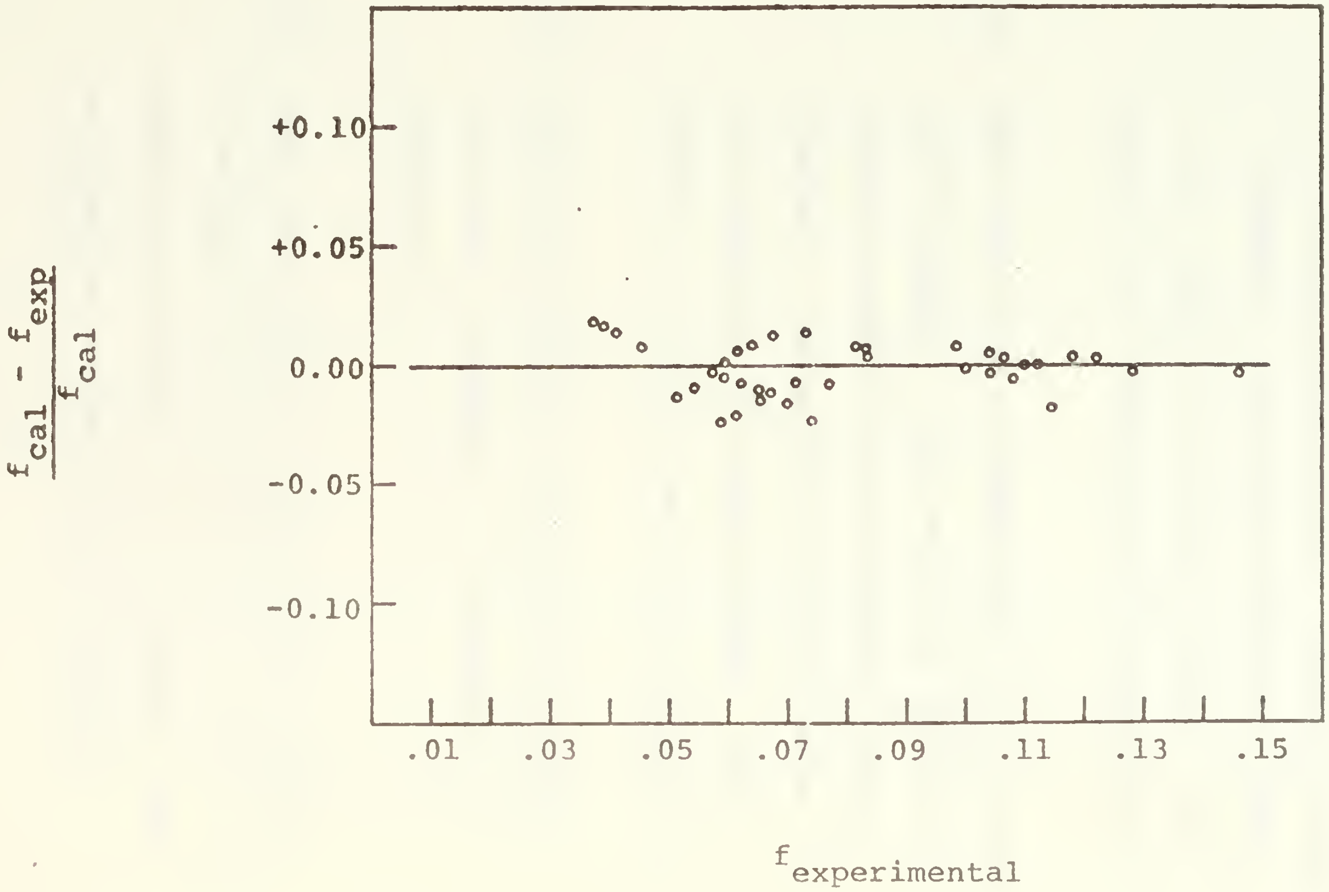


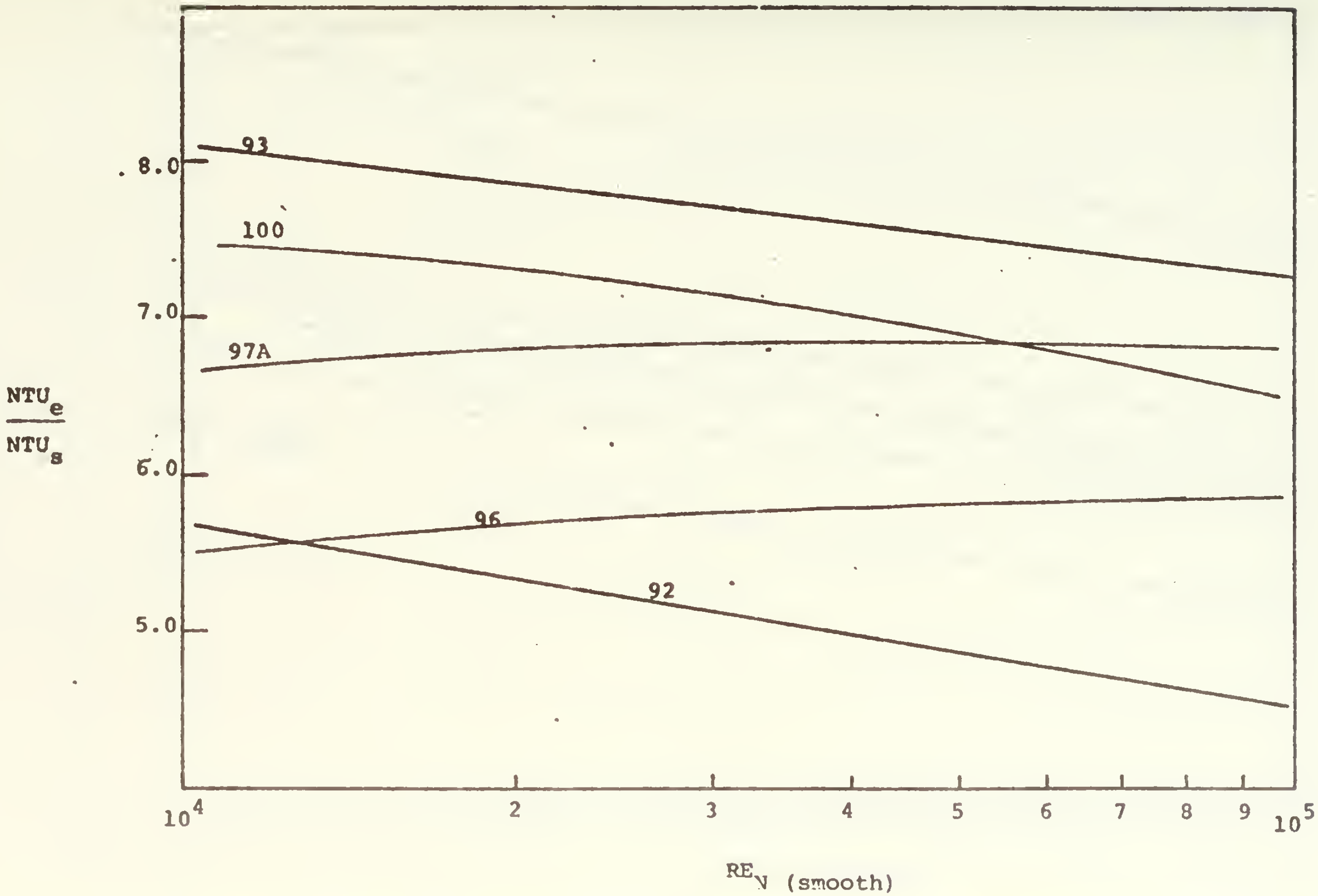
Figure 13: Shows the ratio of ordinates [NTU_e/NTU_s] verses RE_N for Case A. [Same heat exchanger shape and volume] Since both the smooth and enhanced surfaces have identical nominal diameters, the nominal Reynolds number is also identical for each surface. [see equation 27; results read from Appendix II]

Figure 14: Shows the ratio of abscissas [P_e/P_s] verses RE_N for Case A. Since both the smooth and enhanced surfaces have identical nominal diameters, the nominal Reynolds number is also identical for each surface. [see equation 27;results read from Appendix II]

Figure 15: Shows the ratio of ordinates [NTU_e/NTU_s] verses RE_N for Case B. [P=constant and V=constant]

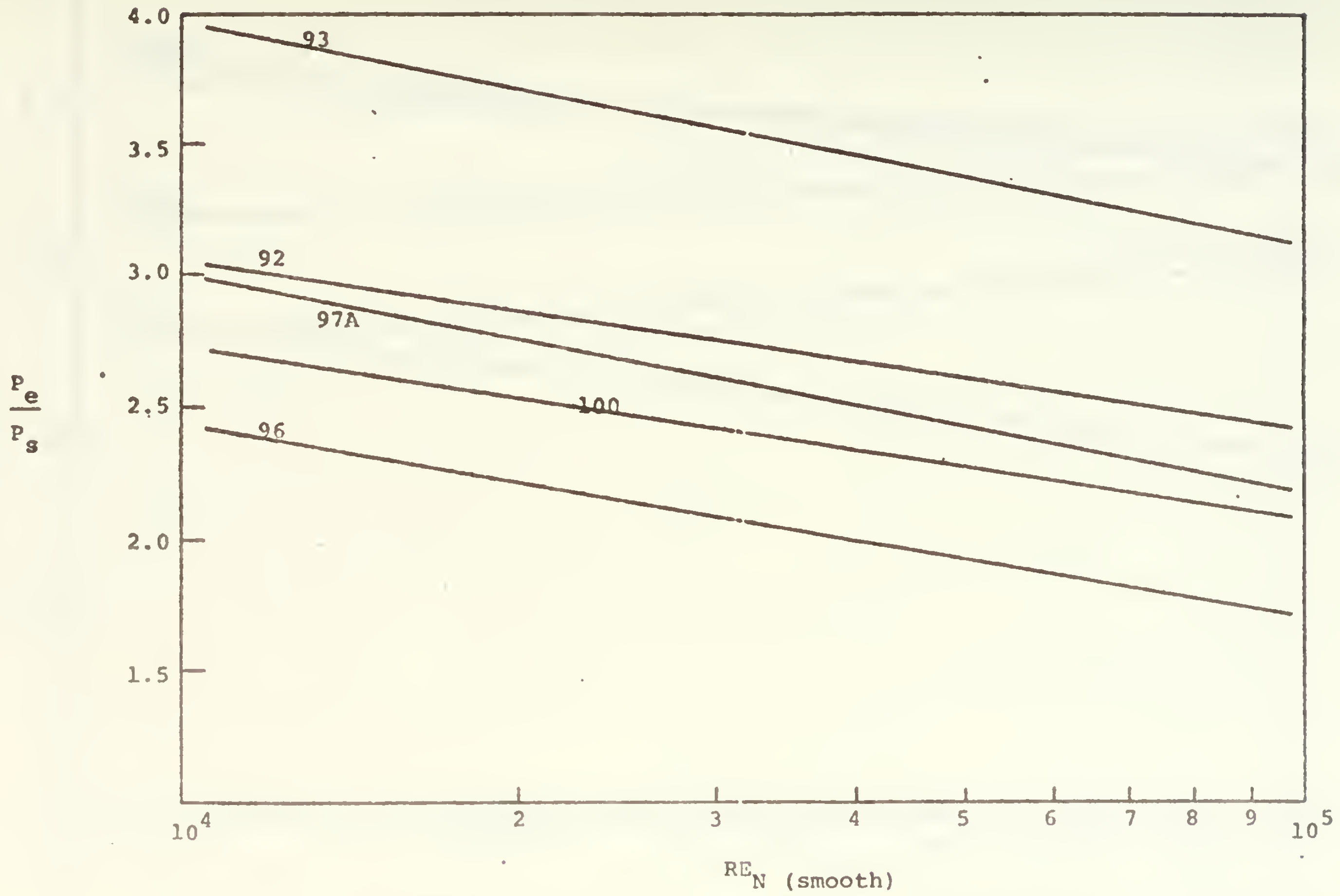
Figure 16: Shows the ratio of abscissas or ordinates to produce [V_s/V_e] verses RE_N. Recall that each axis of Figure 10 is inversely proportional to volume. This is Case C.

FIGURE 13



Performance Comparison Results (NTU_e/NTU_s) for Case A. Both the surfaces have $D_N \approx 1.60$ inches and, therefore, RE_N, is constant.

FIGURE 14



Performance comparison Results (P_e/P_s) for Case A. Both the enhanced and smooth surface have $D_N \approx 1.60$ inches and, therefore, RE_N, is constant.

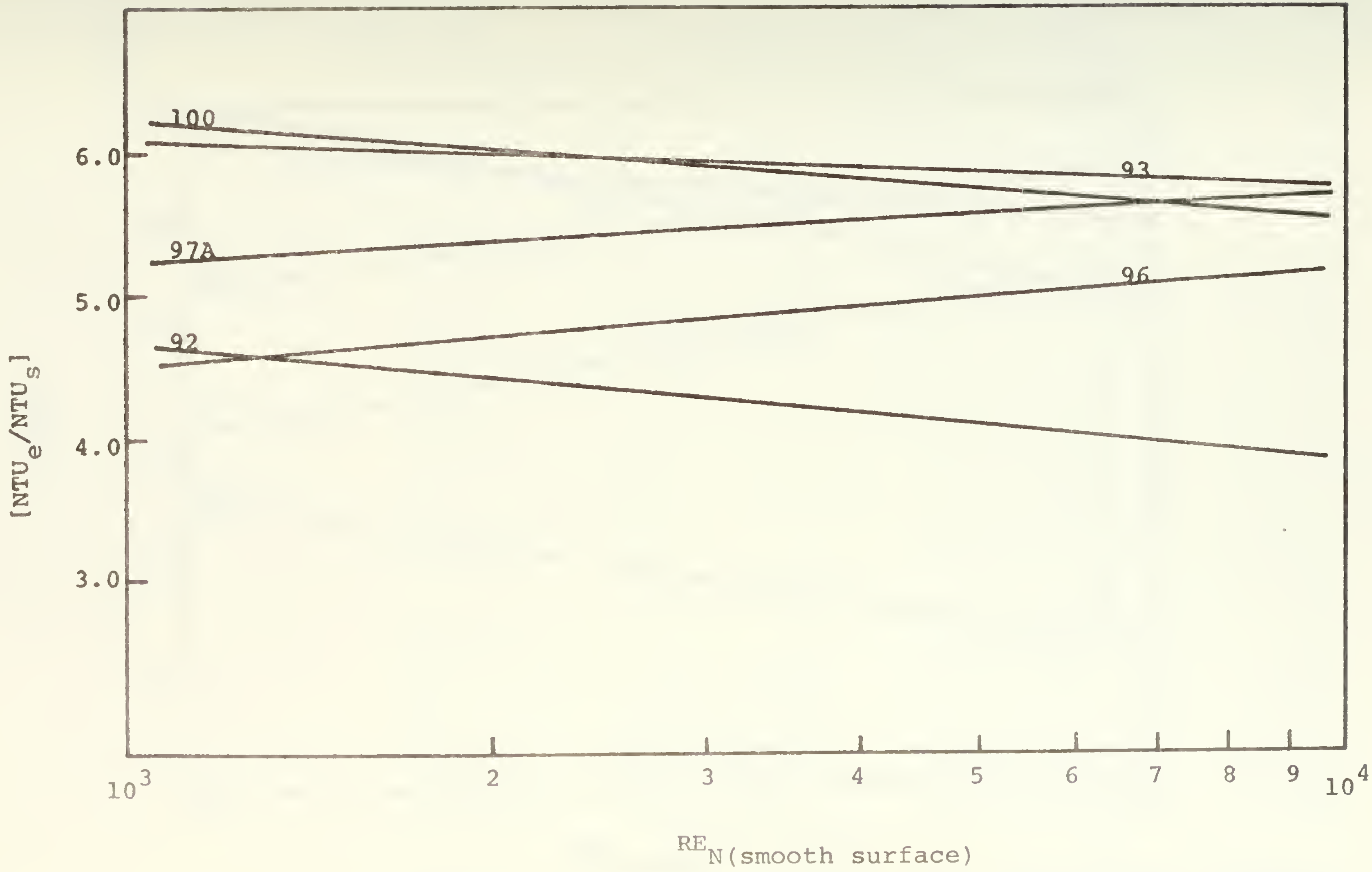


FIGURE 15: Performance Comparison Results for CASE B [i.e. V = Constant and P = constant], $D_N \simeq 1.60$ inches for both enhanced and smooth surfaces.

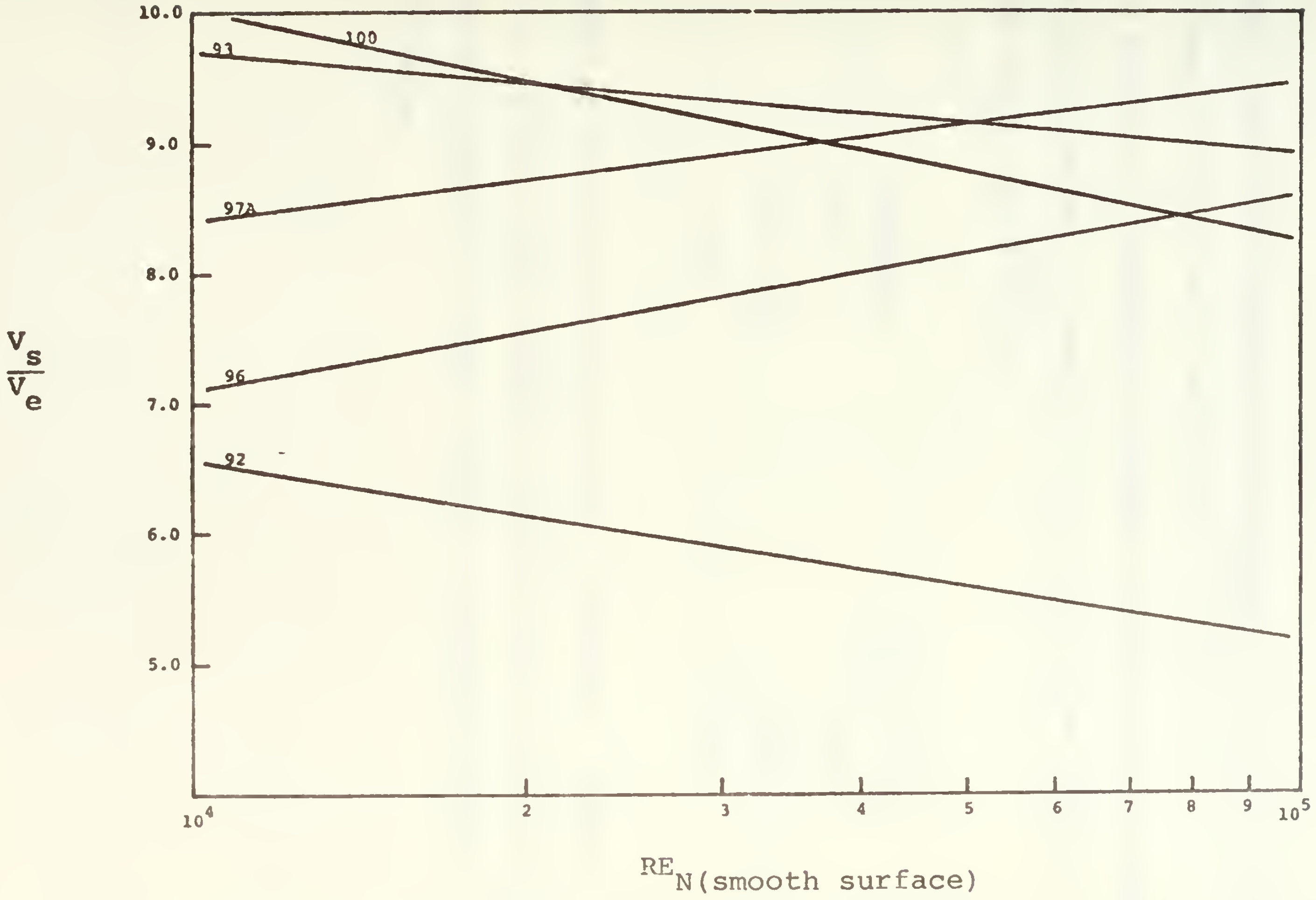


FIGURE 16: Performance comparison results for CASE C [i.e. NTU = constant, P = constant] $D_N \simeq 1.60$ inches for both enhanced & plain surface.

Figure 17: Shows the ratio of abscissas $[P_s/P_e]$ verses RE_N for Case D. [NTU=constant, and V=constant]

Higher ratios are preferred for Figures 13,15,16, and 17 while a lower ratio is most desirable in Figure 14.

As a matter of secondary interest, of the five surfaces with identical nominal diameters, there are three discrete values of the ratio $[A_F\ b]/V_{os}$:

Surface	$[A_F\ b]/V_{os}$
92 & 93	1.4282
96 & 97A	1.1859
100	1.4014

Comparison of many surfaces having identical nominal diameters to a single common smooth surface having the same nominal diameter permits the best relative comparison between enhanced surfaces.

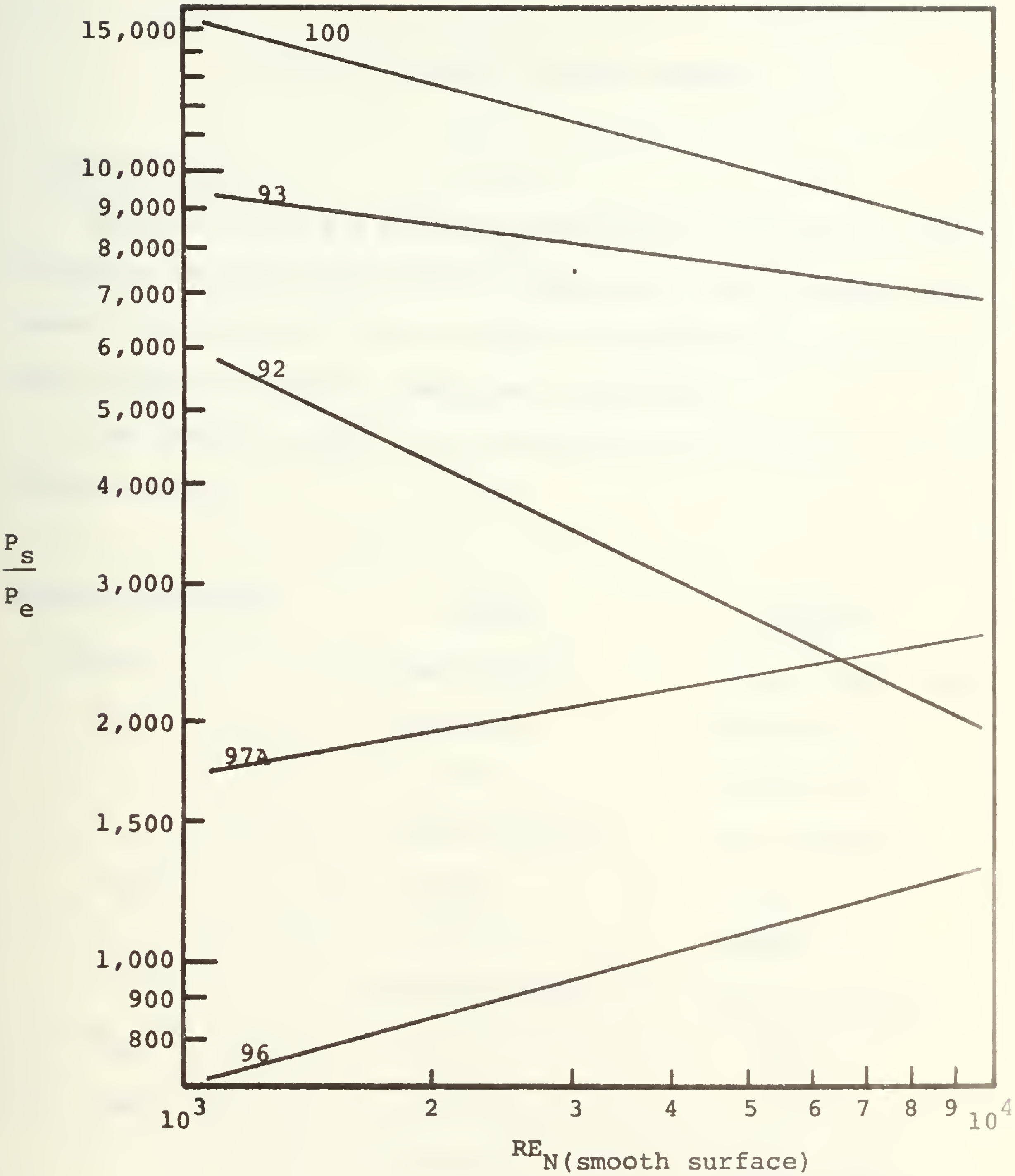


FIGURE 17: Performance comparison results for CASE D [i.e. NTU and V are constant] $D_N \simeq 1.60$ inches for both the enhanced and plain surfaces.

[illegible]

IV. HEAT EXCHANGER DESIGN PROBLEM

A. Description

Appendix III is a procedure which can be used for sizing crossflow finned tubular heat exchangers. The following data, taken from reference [2], is used to determine the required heat exchanger size for the given conditions.

The design is that of an intercooler for a 5000 SHP gas turbine plant.

DESIGN CONSTRAINT	SIDE I	SIDE II
Surface	Smooth Tube	Finned Tube [98C]
D_h	0.0625 FT	0.0445 FT
δ	N/A	0.0010 FT
β	5.9291 FT^2/FT^3	61.9 FT^2/FT^3
A_δ/A_T	N/A	0.8350
ℓ	N/A	0.3445 IN
W	400,000 LB/HR	200,667 LB/HR
T_{in}	60° F	260° F
T_{out}	82° F	80° F
ΔP	1.554 PSI	0.3060 PSI
μ	2.360 LB/HR-FT	0.0482 LB/HR-FT
C_p	1.000 BTU/LB-°F	0.2436 BTU/LB-°F
ρ_m	62.38 LB/FT^3	0.1755 LB/FT^3

DESIGN CONSTRAINT	SIDE I	SIDE II
P_r	6.8000	0.7000
K_m	N/A	222 BTU/HR-FT-°F
F	2.725 IN	N/A
b	1.750 IN	N/A
A_c	0.4418 IN^2	Calculate

Using the design procedure outlined in Appendix III, the principle dimensions are:

$$X = 6.43 \text{ FT}$$

$$Y = 26.11 \text{ FT}$$

$$Z = 0.63 \text{ FT}$$

$$\text{Total Volume} = 105.46 \text{ FT}^3$$

This is a possible heat exchanger design that satifies the given constraints.

B. Attempt to Minimize Total Volume

If minimization of total volume is a required design constraint, the engineer has several options the limits of which might be bounded by:

(A) Design a heat exchanger to the given specifications using each known surface for which f and j data are available. In this study sixteen surfaces are considered.

(B) Noting the marked superiority of reference [2] figure

(B) continued

94, apply the method developed in Chapter II to estimate total volume savings relative to the base or reference heat exchanger designed in part I.

Option (A) will be eliminated as being impractical due to the required effort.

Option (B) will be shown to be the most direct and highly accurate approach.

The f and j verses RE data for reference [2] figure 98C and 94 are presented in Figure 18. The problem presented corresponds to Case C described in Figure 16.

Using the heat exchanger design procedure outlined in Appendix III and replacing the finned tube side with the surface of figure 94 [Ref 2]:

$$X = 1.50 \text{ FT}$$

$$Y = 10.89 \text{ FT}$$

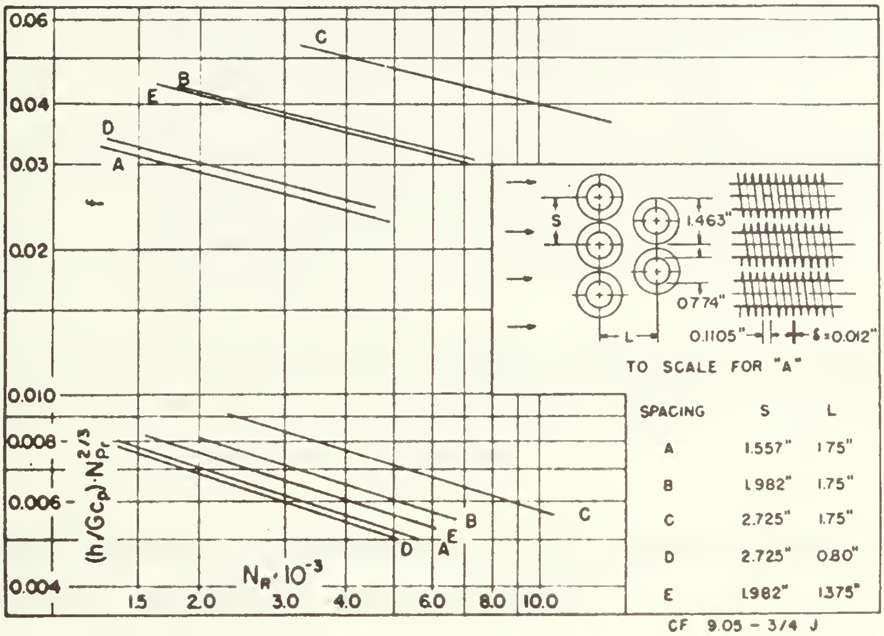
$$Z = 1.76 \text{ FT}$$

$$\text{Total Volume} = 28.68 \text{ FT}^3$$

A 73% reduction in volume would result by employing the surface of figure 94 [Ref 2].

In order to use the comparison method developed in Chapter II to quantitatively predict the volume savings, a performance parameter plot is constructed for each surface considered. Figure 19 presents the only two surfaces being considered in this example.

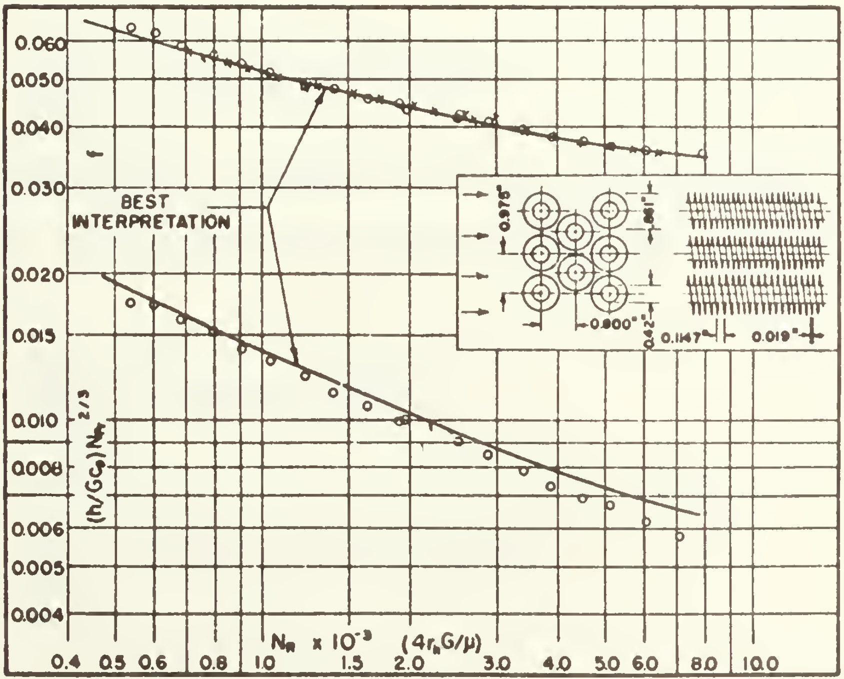
FIGURE 18: f and j verses RE data for the two surfaces considered in the design example.



SPACING	S	L
A	1.557"	1.75"
B	1.982"	1.75"
C	2.725"	1.75"
D	2.725"	0.80"
E	1.982"	1.375"

CF 9.05 - 3/4 J

FIG. 98



CF-8.72 (C)

FIG. 94

As outlined in Chapter II for Case C:

(1) From the design point of the reference heat exchanger (Figure 98C) graphically or analytically construct a line of slope 1.

(2) The intersection of this line with the new surface (Figure 94) will yield the performance parameters at the design point of the new heat exchanger.

(3) The predicted volume reduction is found from the ratio of either the ordinates or abscissas of the two surfaces.

The performance parameters of the reference heat exchanger design are: [Reference 2 figure 98C]

$$\frac{NTU}{V_{os}} = 401.20 \ [1/IN^2]$$

$$\frac{P}{V_{os}} = 2.93 \times 10^{12} \ [1/IN^4]$$

The performance parameters of the heat exchanger that would result from using the surface described by reference[2] figure 94:

$$\frac{NTU}{V_{os}} = 1634.68 \ [1/IN^2]$$

$$\frac{P}{V_{os}} = 1.19 \times 10^{13} \ [1/IN^4]$$

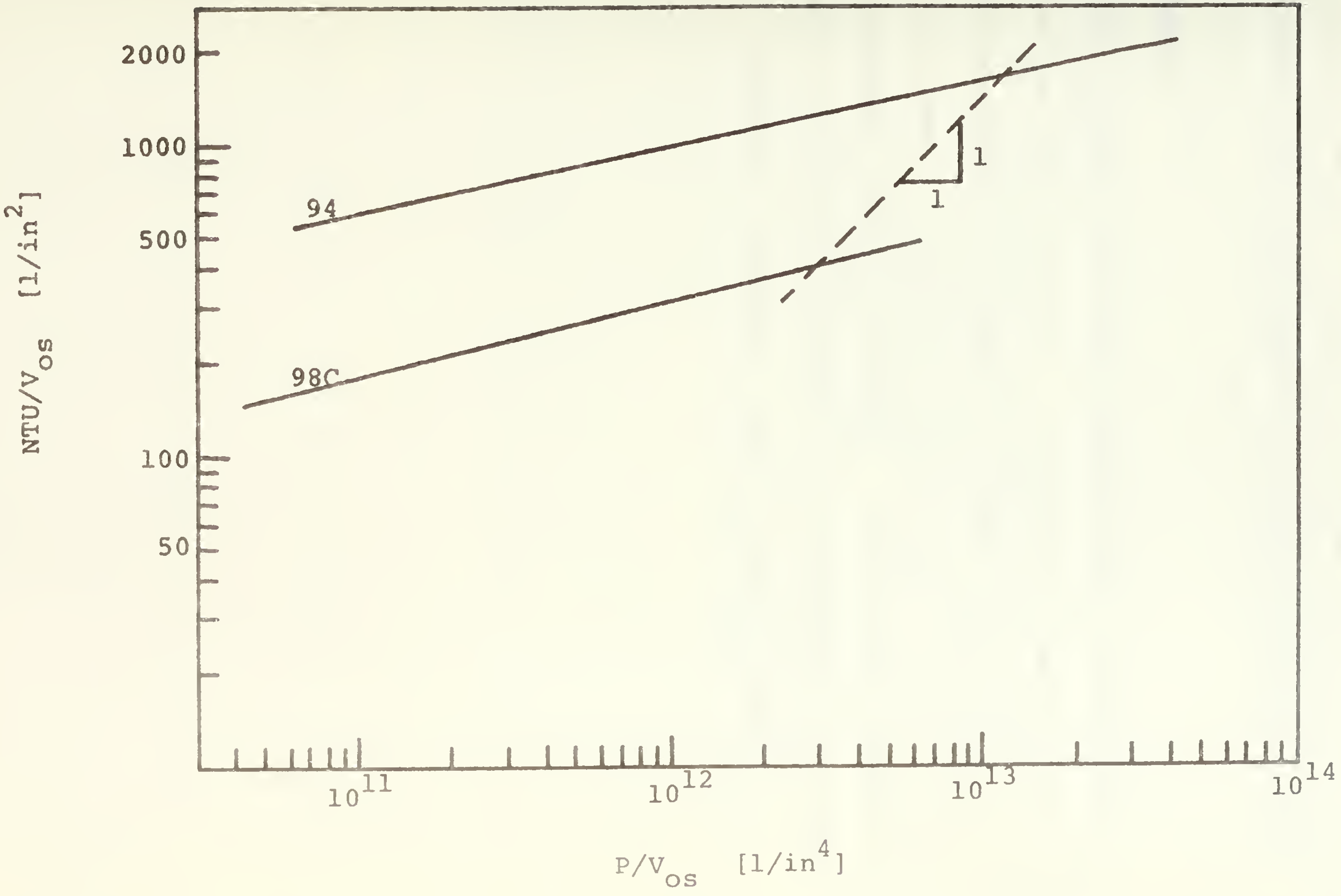


FIGURE 19: Performance Parameter Plot for the two surfaces used in the Design Example

In other words, a predicted volume reduction of 75% is anticipated using the comparison method developed herein.

C. Summary

Two surfaces have been compared from a minimization of total volume point-of-view. It has been shown that the performance parameters developed in Chapter II allow us to compare any number of surfaces without going through a complete heat exchanger design calculation. Where there may well be hundreds of different surfaces to be considered, the value of such a comparison technique cannot be overestimated.

V. CONCLUSIONS

1. The comparison method of Soland [5] was used as a basis in developing a comparison method for finned tube heat exchanger surfaces.

2. Heat Exchanger Performance can be compared on four different bases:

    a. Same shape and volume of heat exchanger

    b. Same exchanger volume and pumping power

    c. Same pumping power and NTU

    d. Same volume and NTU

3. All of Kays and London [2] finned tube surfaces and several surfaces supplied by the Trane Corporation were compared on the above basis.

4. The method developed herein was applied to a practical heat exchanger design problem and found to accurately predict relative volume savings between different surfaces.

REFERENCES

1. Rohsenow, W.M. and Choi, H., Heat, Mass, and Momentum Transfer, Prentice-Hall, Inc., Englewood Cliff, New Jersey, 1961.

2. Kays, W.M. and London, A.L., Compact Heat Exchangers, McGraw-Hill Book Company, Inc., New York, 1958.

3. Kern, D.Q. and Kraus, A.D., Extended Surface Heat Transfer, McGraw-Hill Book Company, Inc., New York, 1972.

4. Rohsenow, W.M. and Hartnett, J.P., Handbook of Heat Transfer, McGraw-Hill Book Company, Inc., New York, 1973.

5. Soland, J.G., "Performance Ranking of Plate Finned Heat Exchanger Surfaces", M.I.T. Ocean Engineering Thesis, May, 1975.

6. Sheldon, E.S., "Heat Exchanger Performance Ranking", M.I.T. Ocean Engineering Thesis, May, 1976.

7. Zhukaukas, A., "Heat Transfer From Tubes in Crossflow", Advances in Heat Transfer, Vol 8, pp 93-160, 1972.

8. Personal communication, Director Research and Development, Harrison Radiator Divison, General Motors Corporation; with W.M. Rohsenow.

9. Mack, W.M., "Evaluation of the Heat Transfer Performance of Three Enhanced Surfaces Including and Enhanced Surface Heat Exchanger Performance Comparison", Ph.D disertation M.I.T., 1974.

REFERENCES (continued)

10. Fraas and Ozisik, Heat Exchanger Design, John Wiley and Sons, Inc., New York, 1965.

APPENDIX I

A. Purpose

A frequent criticism of academic solutions to "optimization" of design is: "So what, . . . how does this help the engineer in industry?" [8]

It is hoped that this section will give the "engineer in industry" the needed background and technique to effectively compare finned tubular heat exchanger surfaces.

A step-by-step flow diagram using the performance comparison equations derived in the text of the thesis is presented in Figure A-1. This procedure is easily programmed for use on either a (1) standard computer or (2) programmable calculator.

In keeping with the spirit of the criticism of Reference [8], a program for use on a personal programmable calculator will be presented herein. It is intended that this simplified, easy-to-use approach will demonstrate that the "engineer in industry" needn't resort to often costly computer time/programs in order to effectively "optimize" a design.

B. Proposed Program(s) for Calculating Surface Performance Parameters on a Programmable* Calculator

The following programs follow the general outline of Figure A-1:

Figure A-II: For calculating Surface Performance Parameters for the case in which the

CALCULATION OF FINNED TUBULAR HEAT EXCHANGER SURFACE PERFORMANCE PARAMETERS

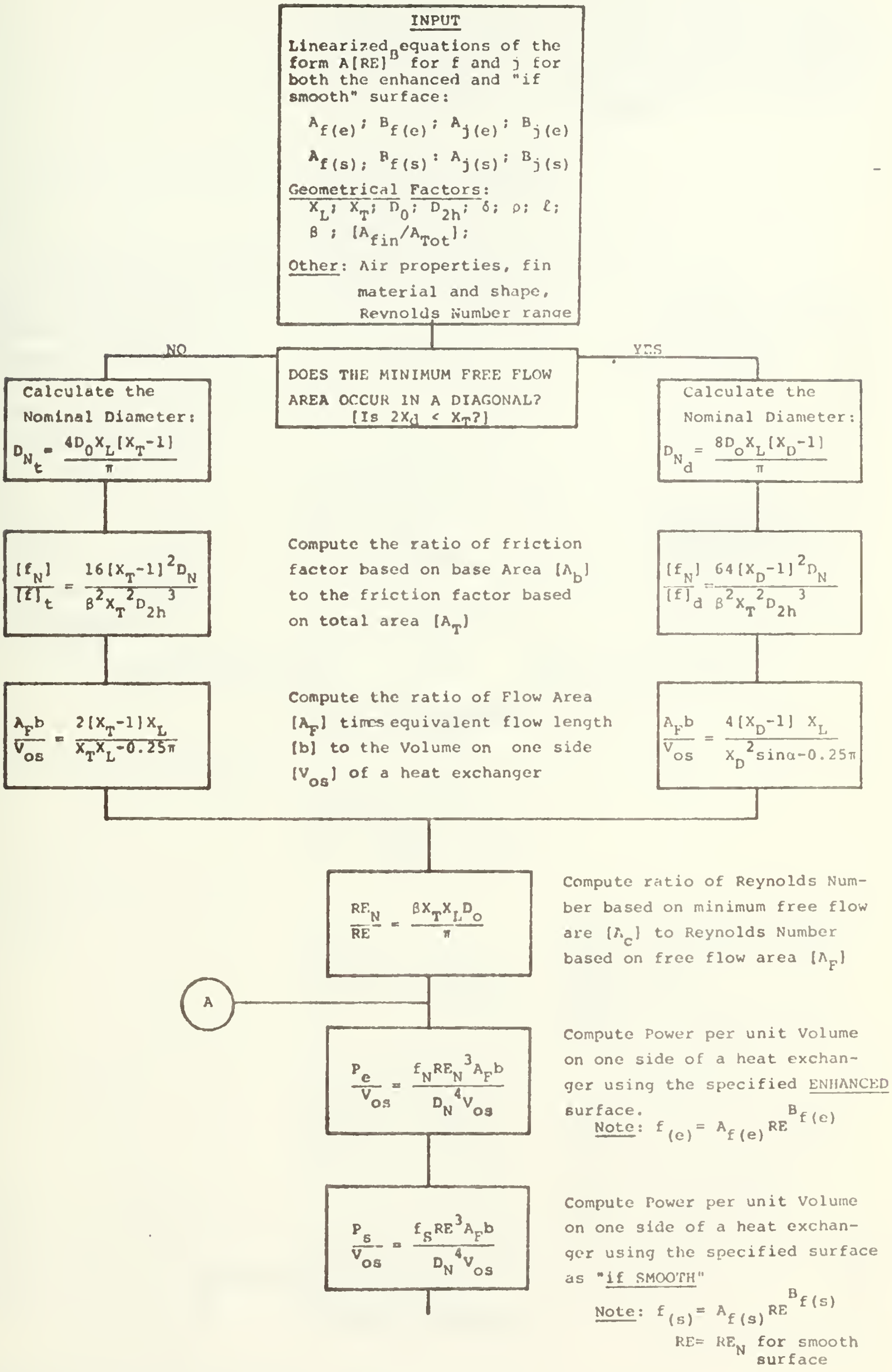
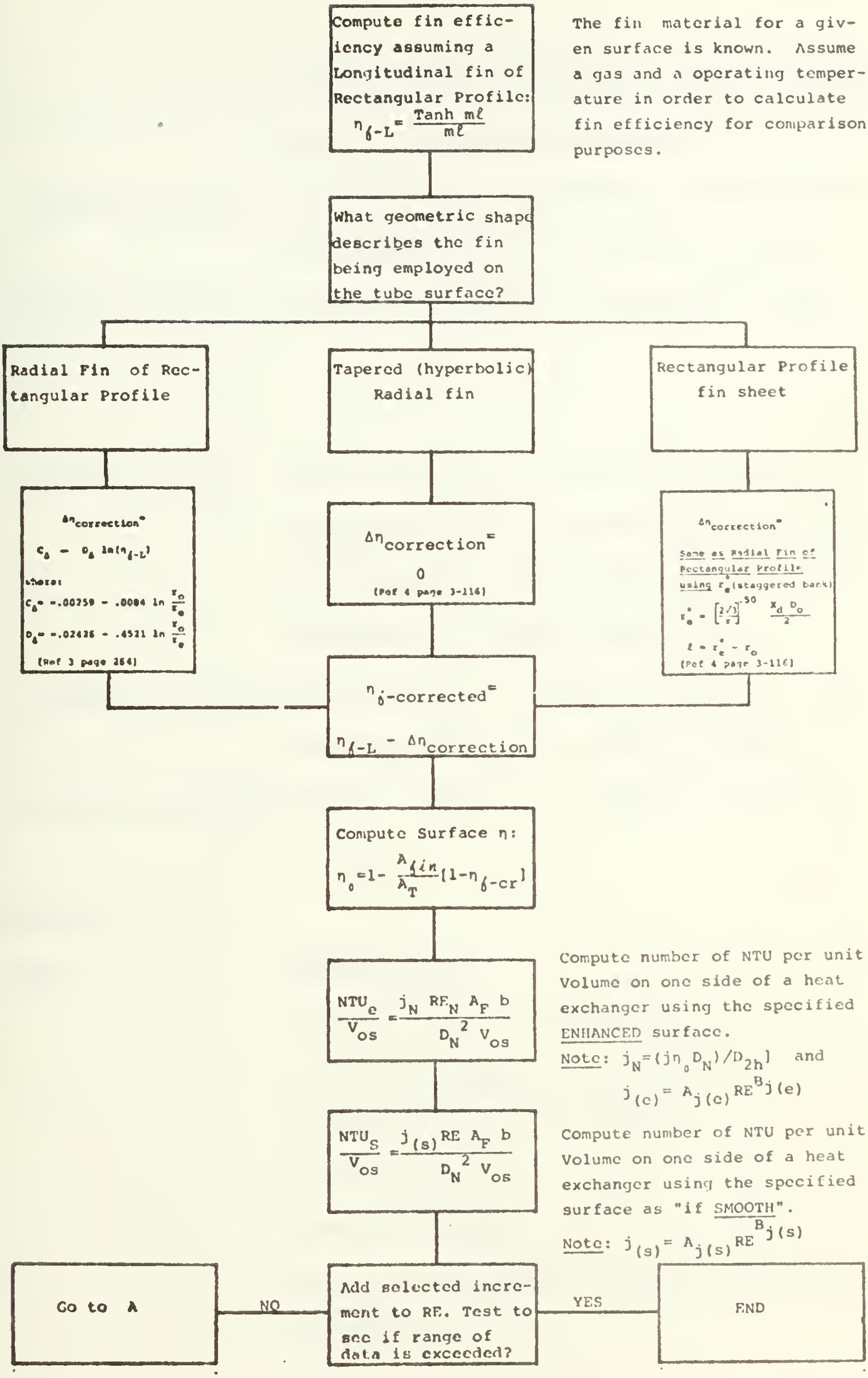

INPUT
Linearized equations of the form $A[RE]^{B}$ for f and j for both the enhanced and "if smooth" surface:
$A_{f(e)}$; $B_{f(e)}$; $A_{j(e)}$; $B_{j(e)}$
$A_{f(s)}$; $B_{f(s)}$; $A_{j(s)}$; $B_{j(s)}$
Geometrical Factors:
X_L; X_T; D_0; D_{2h}; δ; ρ; ℓ;
β; $[A_{fin}/A_{Tot}]$;
Other: Air properties, fin material and shape, Reynolds Number range
NO
YES
DOES THE MINIMUM FREE FLOW AREA OCCUR IN A DIAGONAL? [Is $2X_d < X_T$?]
Calculate the Nominal Diameter:
$D_{N_t} = \frac{4D_0 X_L [X_T - 1]}{\pi}$
Calculate the Nominal Diameter:
$D_{N_d} = \frac{8D_o X_L [X_D - 1]}{\pi}$
$\frac{[f_N]}{[f]_t} = \frac{16[X_T - 1]^2 D_N}{\beta^2 X_T^2 D_{2h}^3}$
Compute the ratio of friction factor based on base Area $[A_b]$ to the friction factor based on total area $[A_T]$
$\frac{[f_N]}{[f]_d} = \frac{64[X_D - 1]^2 D_N}{\beta^2 X_T^2 D_{2h}^3}$
$\frac{A_F b}{V_{os}} = \frac{2[X_T - 1]X_L}{X_T X_L - 0.25\pi}$
Compute the ratio of Flow Area $[A_F]$ times equivalent flow length [b] to the Volume on one side $[V_{os}]$ of a heat exchanger
$\frac{A_F b}{V_{os}} = \frac{4[X_D - 1]\ X_L}{X_D^2 \sin\alpha - 0.25\pi}$
$\frac{RE_N}{RE} = \frac{\beta X_T X_L D_o}{\pi}$
Compute ratio of Reynolds Number based on minimum free flow are $[A_c]$ to Reynolds Number based on free flow area $[A_F]$
A
$\frac{P_e}{V_{os}} = \frac{f_N RE_N^3 A_F b}{D_N^4 V_{os}}$
Compute Power per unit Volume on one side of a heat exchanger using the specified ENHANCED surface.
Note: $f_{(e)} = A_{f(e)} RE^{B_{f(e)}}$
$\frac{P_s}{V_{os}} = \frac{f_s RE^3 A_F b}{D_N^4 V_{os}}$
Compute Power per unit Volume on one side of a heat exchanger using the specified surface as "if SMOOTH"
Note: $f_{(s)} = A_{f(s)} RE^{B_{f(s)}}$
$RE = RE_N$ for smooth surface

FIGURE A-1: Performance Parameters


Compute fin efficiency assuming a Longitudinal fin of Rectangular Profile:
$\eta_{f-L} = \frac{\tanh m\ell}{m\ell}$
What geometric shape describes the fin being employed on the tube surface?
Radial Fin of Rectangular Profile
Tapered (hyperbolic) Radial fin
Rectangular Profile fin sheet
$\Delta\eta_{correction} = C_\delta - D_\delta \ln(\eta_{f-L})$
where:
$C_\delta = -.00259 - .0004 \ln \frac{r_o}{r_e}$
$D_\delta = -.02436 - .4521 \ln \frac{r_o}{r_e}$
(Ref 3 page 264)
$\Delta\eta_{correction} = 0$
(Ref 4 page 3-116)
$\Delta\eta_{correction} =$
Same as Radial Fin of Rectangular Profile using $\dot{r}_e$ (staggered bank)
$\dot{r}_e = \left[\frac{2/3}{r}\right]^{.50} \frac{X_d D_o}{2}$
$\ell = \dot{r}_e - r_o$
(Ref 4 page 3-116)
$\eta_{f\text{-corrected}} = \eta_{f-L} - \Delta\eta_{correction}$
Compute Surface η:
$\eta_o = 1 - \frac{A_{fin}}{A_T}[1 - \eta_{f-cr}]$
$\frac{NTU_e}{V_{os}} = \frac{j_N \, RE_N \, A_F \, b}{D_N^2 \, V_{os}}$
$\frac{NTU_S}{V_{os}} = \frac{j_{(s)} RE \, A_F \, b}{D_N^2 \, V_{os}}$
Add selected increment to RE. Test to see if range of data is exceeded?
NO
Go to A
YES
END

The fin material for a given surface is known. Assume a gas and a operating temperature in order to calculate fin efficiency for comparison purposes.

Compute number of NTU per unit Volume on one side of a heat exchanger using the specified ENHANCED surface.

Note: $j_N = (j\eta_o D_N)/D_{2h}]$ and

$j_{(e)} = A_{j(e)} RE^{B_{j(e)}}$

Compute number of NTU per unit Volume on one side of a heat exchanger using the specified surface as "if SMOOTH".

Note: $j_{(s)} = A_{j(s)} RE^{B_{j(s)}}$

minimum free flow area occurs transversely to the flow direction.

Figure A-II-A: Definition of geometric constraints/ constants to be stored in memory.

Figure A-II-B: Sample output for transverse case.

Figure A-III: For calculating Surface Performance Parameters for the case in which the minimum free flow area occurs in the diagonals. [see Figure 4]

Figure A-III-A: Definition of geometric constraints/ constants to be stored in memory.

Figure A-III-B: Sample output for diagonal case.

C. Operation

Step	Description
1.	Select and Load Program
2.	Store Constants as outlined in either Figure A-II-A or A-III-A.
3.	Press Key A
4.	Compile Output
5.	Stop Program when range of RE data is exceeded.

PROGRAM* FOR CALCULATING SURFACE PERFORMANCE PARAMETERS FOR A CROSSFLOW FINNED TUBULAR HEAT EXCHANGER IN WHICH THE MINIMUM FREE FLOW AREA OCCURS TRANSVERSLY TO THE FLOW DIRECTION

FIGURE A-II

```
001  *LBLA   21 11
002   RCLA   36 11
003   PRTX     -14
004    SPC   16-11
005   RCLD   36 14
006   RCLC   36 13
007      ×     -35
008      4      04
009      ×     -35
010     Pi   16-24
011      ÷     -24
012   RCLE   36 15
013      1      01
014      -     -45
015      ×     -35
016   STOA   35 11
017   RCLD   36 14
018   RCLE   36 15
019      ×     -35
020   RCLB   36 12
021      ×     -35
022   RCLC   36 13
023      ×     -35
024     Pi   16-24
025      ÷     -24
026   STOC   35 13
027   RCLI   36 46
028    X⇄Y     -41
029      ÷     -24
030   STOI   35 46
031      1      01
032      6      06
033   RCLB   36 12
034   RCLE   36 15
035      ×     -35
036     X²      53
037      ÷     -24
038   RCL5   36 05
039      3      03
040     Yˣ      31
041      ÷     -24
042   RCLE   36 15
043      1      01
044      -     -45
045     X²      53
046      ×     -35
047   RCLA   36 11
048      ×     -35
049   STOB   35 12
050   RCLE   36 15
051   RCLD   36 14
052      ×     -35
053     Pi   16-24
054      4      04
055      ÷     -24
056      -     -45

057      2      02
058    X⇄Y     -41
059      ÷     -24
060   RCLE   36 15
061      1      01
062      -     -45
063      ×     -35
064   RCLD   36 14
065      ×     -35
066   STOE   35 15
067    P⇄S   16-51
068   RCL9   35 09
069     LN      32
070    P⇄S   16-51
071   RCL9   36 09
072      ×     -35
073   RCL8   36 08
074      +     -55
075   STO8   35 08
076    P⇄S   16-51
077   RCL9   36 09
078     LN      32
079    P⇄S   16-51
080   RCL7   36 07
081      ×     -35
082   RCL6   36 06
083      +     -55
084   STO6   35 06
085   PREG   16-13
086    P⇄S   16-51
087   PREG   16-13
088    P⇄S   16-51
089  *LBLC   21 13
090   RCLI   35 46
091   RCL0   36 00
092      +     -55
093   STO0   35 00
094   PRTX     -14
095   RCL2   36 02
096     Yˣ      31
097   RCL1   36 01
098      ×     -35
099   RCLB   36 12
100      ×     -35
101   RCLA   36 11
102      4      04
103     Yˣ      31
104      ÷     -24
105   RCL0   36 00
106   RCLC   36 13
107      ×     -35
108   PRTX     -14
109      3      03
110     Yˣ      31
111      ×     -35
112   RCLE   36 15

113      ×     -35
114   PRTX     -14
115   RCL0   35 00
116   RCLC   36 13
117      ×     -35
118   RCL4   36 04
119      3      03
120      +     -55
121     Yˣ      31
122   RCLA   35 11
123      4      04
124     Yˣ      31
125      ÷     -24
126   RCL3   36 03
127      ×     -35
128   RCLE   36 15
129      ×     -35
130   PRTX     -14
131   RCL0   36 00
132    P⇄S   16-51
133   RCL4   36 04
134      1      01
135      +     -55
136      2      02
137      ÷     -24
138     Yˣ      31
139   RCL3   36 03
140      2      02
141      ×     -35
142   RCL2   36 02
143      ×     -35
144   RCL5   36 05
145      ÷     -24
146    P⇄S   16-51
147   RCL5   35 05
148      ÷     -24
149    P⇄S   16-51
150     √X      54
151      ×     -35
152   RCL1   36 01
153      ×     -35
154   STOD   35 14
155     eˣ      33
156   RCLD   36 14
157    CHS     -22
158     eˣ      33
159      -     -45
160   LSTX   16-63
161   RCLD   35 14
162     eˣ      33
163      +     -55
164      ÷     -24
165   RCLD   36 14
166      ÷     -24
167   ENT↑     -21
168     LN      32

169    P⇄S   16-51
170   RCL8   36 08
171    CHS     -22
172      ×     -35
173   RCL6   36 06
174      +     -55
175    P⇄S   16-51
176   RCL8   36 08
177      ×     -35
178      +     -55
179   PRTX     -14
180   RCL0   36 00
181      ×     -35
182   RCL0   36 00
183      -     -45
184      1      01
185      +     -55
186   RCL3   36 03
187      ×     -35
188    P⇄S   16-51
189   RCL5   35 05
190      ÷     -24
191   RCLA   36 11
192      ÷     -24
193   RCLC   36 13
194      ×     -35
195   RCL0   35 00
196      1      01
197    P⇄S   16-51
198   RCL4   36 04
199      +     -55
200     Yˣ      31
201      ×     -35
202   RCLE   36 15
203      ×     -35
204   PRTX     -14
205    P⇄S   16-51
206   RCL0   35 00
207   RCLC   36 13
208      ×     -35
209    P⇄S   16-51
210   RCL7   35 07
211      1      01
212      +     -55
213     Yˣ      31
214   RCL6   36 06
215      ×     -35
216   RCLA   36 11
217     X²      53
218      ÷     -24
219   RCLE   35 15
220      ×     -35
221   PRTX     -14
222    SPC   16-11
223    P⇄S   16-51
224   STOC   35 13
```

*For Hewlett-Packard 67/97 Programmable Calculator

FIGURE A-II-A

GEOMETRIC CONSTRAINTS/CONSTANTS TO BE STORED IN MEMORY

[Transverse Case]

REG	QTY	DESCRIPTION	REG	QTY	DESCRIPTION
0	RE	Leave Blank. This register is used in the program to store the value of RE being used in each iteration.	10	A_f/A_T	Ratio of fin area to total area.
1	$A_{f(e)}$	From linearized equation for friction factor (f) of the enhanced surface of the form: $A\ RE^B$	11	ℓ	Fin length [inches]
2	$B_{f(e)}$	From linearized equation for friction factor (f) of the enhanced surface of the form: $A\ RE^B$	12	ψ	Property constant defined by: $[C_p\ \mu]/[K_m\ P_r^{2/3}]$ [ND]
3	$A_{f(s)}$	From linearized equation for friction factor (f) of the if smooth surface of the form: $A\ RE^B$	13	$A_{j(e)}$	From linearized equation for Colburn modulus (j) of the enhanced surface of the form: $A\ RE^B$
4	$B_{f(s)}$	From linearized equation for friction factor (f) of the if smooth surface of the form: $A\ RE^B$	14	$B_{j(e)}$	From linearized equation for Colburn modulus (j) of the enhanced surface of the form: $A\ RE^B$
5	D_{2h}	Specified hydraulic diameter of the flow passage [inches]	15	δ	Specified fin thickness or average thickness, if tapered. [inches]
6	a_1	Constants derived from graph on page 244 of Reference [3]. They are used in the computation of a correction factor applied to η_{f-L} in order to permit the use of the simplier $\frac{\tanh m\ell}{m\ell}$ equation for fin temperature effectiveness in lieu of Bessel function type equations.	16	$A_{j(s)}$	From linearized equation for Colburn modulus (j) of the "if smooth" surface of the form: $A\ RE^B$
7	a_2		17	$B_{j(s)}$	From linearized equation for Colburn Modulus (j) of the "if smooth" surface of the form: $A\ RE^B$
8	a_3		18	Fin ID	Input one: 0.000 if fin is tapered -1.000 if fin is a radial fin of rectangular profile
9	a_4		19	ρ	Ratio of outside tube radius to outside fin radius.
A	Data ID	Any desired number to permit the user to identify the surface being processed.	D	X_L	Longitudinal tube pitch. Ratio of longitudinal tube spacing to tube outside diameter.
B	β	Specified heat transfer area per total volume ratio. [in^2/in^3]	E	X_T	Transverse tube pitch. Ratio of transverse tube spacing to tube outside diameter.
C	D_o	Specified tube outside diameter. [inches]	I	Increment	Desired increment of RE_N. A value of 10,000 is recommneded.

FIGURE A-II-B

SAMPLE OUTPUT

[Transverse Case]

```
FIGURE ID# ----------> 100.0000

                         0.0000   0      Print out of Regis-
                         0.1223   1
                        -0.2073   2      ters 0-9 and A-I
                         0.3514   3
                        -0.0896   4
                         0.1430   5
                         0.0054   6
                        -0.0084   7
                         0.4098   8
                        -0.4521   9
                         1.6402   A <--- D_N
f_N/f ----------------> 14.4115   B
                        10.2285   C <--- RE_N/RE
                         2.1542   D
[A_F b]/V_os ---------->  1.4014   E
                       977.6564   I

                         0.8390   0      Print out of Regis-
                         0.3240   1
                         0.0001   2      ters 10-19 and A-I
                         0.1650   3
                        -0.3986   4
                         0.0130   5
                         0.5830   6
                        -0.3960   7
                        -1.0000   8
                         0.3829   9
Value of RE_N being
processed         \
                       977.6564 <--- Value of RE being
                     10000.0000        processed
                 8.186009734+10 <--- P_e/V_os
P_s/V_os ------> 2.981639001+10
                         0.9328 <--- η_f-corrected
NTU_e/V_os ----------> 598.0269
                        79.1432 <--- NTU_s/V_os
```

FIGURE A-III

PROGRAM* FOR CALCULATING SURFACE PERFORMANCE PARAMETERS FOR A CROSSFLOW FINNED TUBULAR HEAT EXCHANGER IN WHICH THE MINIMUM FREE FLOW AREA OCCURS IN THE DIAGONALS

```
001  *LBLA     21 11
002   RCLA     36 11
003   PRTX       -14
004   RCL0     36 00
005     X²        53
006   RCLE     36 15
007    SIN        41
008      ×       -35
009     Pi     16-24
010      4        04
011      ÷       -24
012      -       -45
013      4        04
014    X≷Y       -41
015      ÷       -24
016   RCL0     36 00
017      1        01
018      -       -45
019      ×       -35
020   RCLD     36 14
021      ×       -35
022   STOE     35 15
023   RCLD     36 14
024   RCLC     36 13
025      ×       -35
026      8        08
027      ×       -35
028     Pi     16-24
029      ÷       -24
030   RCL0     36 00
031      1        01
032      -       -45
033      ×       -35
034   STOA     35 11
035   RCLD     36 14
036   RCLC     36 13
037      ×       -35
038   RCLB     36 12
039      ×       -35
040     Pi     16-24
041      ÷       -24
042    P≷S     16-51
043   RCL5     36 05
044      ×       -35
045   STOC     35 13
046   RCLI     36 46
047    X≷Y       -41
048      ÷       -24
049   STOI     35 46
050      6        06
051      4        04
052   RCLB     36 12
053   RCL5     36 05
054      ×       -35
055     X²        53
056      ÷       -24
057    P≷S     16-51
058   RCL5     36 05
059      3        03
060     Yˣ        31
061      ÷       -24
062   RCL0     36 00
063      1        01
064      -       -45
065     X²        53
066      ×       -35
067   RCLA     36 11
068      ×       -35
069   STOB     35 12
070    P≷S     16-51
071   RCL9     36 09
072     LN        32
073    P≷S     16-51
074   RCL9     36 09
075      ×       -35
076   RCL8     36 08
077      +       -55
078   STO8     35 08
079    P≷S     16-51
080   RCL9     36 09
081     LN        32
082    P≷S     16-51
083   RCL7     36 07
084      ×       -35
085   RCL6     36 06
086      +       -55
087   STO6     35 06
088   PREG     16-13
089    P≷S     16-51
090   PREG     16-13
091    P≷S     16-51
092      0        00
093   STO0     35 00
094  *LBLC     21 13
095   RCLI     36 46
096   RCL0     36 00
097      +       -55
098   STO0     35 00
099   RCL2     36 02
100     Yˣ        31
101   RCL1     36 01
102      ×       -35
103   RCLB     36 12
104      ×       -35
105   RCLA     36 11
106      4        04
107     Yˣ        31
108      ÷       -24
109   RCL0     36 00
110   RCLC     36 13
111      ×       -35
112   PRTX       -14
113      3        03
114     Yˣ        31
115      ×       -35
116   RCLE     36 15
117      ×       -35
118   PRTX       -14
119   RCL0     36 00
120   RCLC     36 13
121      ×       -35
122   RCL4     36 04
123      3        03
124      +       -55
125     Yˣ        31
126   RCLA     36 11
127      4        04
128     Yˣ        31
129      ÷       -24
130   RCL3     36 03
131      ×       -35
132   RCLE     36 15
133      ×       -35
134   PRTX       -14
135   RCL0     36 00
136    P≷S     16-51
137   RCL1     36 01
138      1        01
139      +       -55
140      2        02
141      ÷       -24
142     Yˣ        31
143   RCL3     36 03
144      2        02
145      ×       -35
146   RCL2     36 02
147      ×       -35
148    P≷S     16-51
149   RCL5     36 05
150      ÷       -24
151    P≷S     16-51
152     √X        54
153      ×       -35
154   RCL1     36 01
155      ×       -35
156   STOD     35 14
157     eˣ        33
158   RCLD     36 14
159    CHS       -22
160     eˣ        33
161      -       -45
162   LSTX     16-63
163   RCLD     36 14
164     eˣ        33
165      +       -55
166      ÷       -24
167   RCLD     36 14
168      ÷       -24
169   ENT↑       -21
170     LN        32
171    P≷S     16-51
172   RCL8     36 08
173      ×       -35
174   RCL6     36 06
175      +       -55
176    P≷S     16-51
177   RCL9     36 09
178      ×       -35
179      +       -55
180   RCL0     36 00
181      ×       -35
182   RCL0     36 00
183      -       -45
184      1        01
185      +       -55
186   RCL3     36 03
187      ×       -35
188    P≷S     16-51
189   RCL5     36 05
190      ÷       -24
191   RCLA     36 11
192      ÷       -24
193   RCLC     36 13
194      ×       -35
195   RCL0     36 00
196      1        01
197    P≷S     16-51
198   RCL4     36 04
199      +       -55
200     Yˣ        31
201      ×       -35
202   RCLE     36 15
203      ×       -35
204   PRTX       -14
205    P≷S     16-51
206   RCL0     36 00
207   RCLC     36 13
208      ×       -35
209    P≷S     16-51
210   RCL7     36 07
211      1        01
212      +       -55
213     Yˣ        31
214   RCL6     36 06
215      ×       -35
216   RCLA     36 11
217     X²        53
218      ÷       -24
219   RCLE     36 15
220      ×       -35
221   PRTX       -14
222    SPC     16-11
223    P≷S     16-51
224   GTOC     22 13
```

*For Hewlett-Packard 67/97 Programmable Calculator

FIGURE A-III-A

GEOMETRIC CONSTRAINTS/CONSTANTS TO BE STORED IN MEMORY

[Diagonal Case]

REG	QTY	DESCRIPTION	REG	QTY	DESCRIPTION
0	X_D	Specified diagonal tube pitch. Ratio of diagonal tube spacing to the tube outside diameter.	10	A_f/A_T	Ratio of fin area to total area.
1	$A_{f(e)}$	From linearized equation for friction factor (f) of the enhanced surface of the form: $A\ RE^B$	11	$\ell/\sqrt{\delta}$	Ratio of fin length to fin thickness. $[1/\sqrt{\text{inch}}]$
2	$B_{f(e)}$	From linearized equation for friction factor (f) of the enhanced surface of the form: $A\ RE^B$	12	¶	Property constant defined by: $[C_p\ \mu]/[K_m\ P_r^{2/3}]$ [ND]
3	$A_{f(s)}$	From linearized equation for friction factor (f) of the if smooth surface of the form: $A\ RE^B$	13	$A_{j(e)}$	From linearized equation for Colburn modulus (j) of the enhanced surface of the form: $A\ RE^B$
4	$B_{f(s)}$	From linearized equation for friction factor (f) of the if smooth surface of the form: $A\ RE^B$	14	$B_{j(e)}$	From linearized equation for Colburn modulus (j) of the enhanced surface of the form: $A\ RE^B$
5	D_{2h}	Specified hydraulic diameter of the flow passage [inches]	15	X_T	Transverse tube pitch. Ratio of transverse tube spacing to tube outside diameter.
6	Δ_1	Constants derived from graph on page 264 of Reference [3]. They are used in the computation of a correction factor applied to η_{f-L} in order to permit the use of the simplier $\frac{\text{Tanh } m\ell}{m\ell}$ equation for fin temperature effectiveness in lieu of Bessel function type equations.	16	$A_{j(s)}$	From linearized equation for Colburn modulus (j) of the "if smooth" surface of the form: $A\ RE^B$
7	Δ_2		17	$B_{j(s)}$	From linearized equation for Colburn Modulus (j) of the "if smooth" surface of the form: $A\ RE^B$
8	Δ_3		18	Fin ID	Input one: 0.000 if fin is tapered -1.000 if fin is a radial fin of rectangular profile
9	Δ_4		19	ρ	Ratio of outside tube radius to outside fin radius.
A	Data ID	Any desired number to permit the user to identify the surface being processed.	D	X_L	Longitudinal tube pitch. Ratio of longitudinal tube spacing to tube outside diameter.
B	β	Specified heat transfer area per total volume ratio. $[\text{in}^2/\text{in}^3]$	E	α	Angle defined by longitudinal centerline and diagonal centerline: [degrees]
C	D_o	Specified tube outside diameter. [inches]	I	Increment	Desired increment of RE_N. A value of 10,000 is recommneded.

FIGURE A-IIIB

SAMPLE OUTPUT

[diagonal case]

```
      FIGURE ID# ----------> 98.4000        Print out of Regis-
                                            ters 0-9 and A-I
                             2.0413    0
                             0.2173    1
                            -0.2590    2
                             1.1125    3
                            -0.1971    4
                             0.1904    5
                             0.0027    6
                            -0.0084    7
                             0.2636    8
                            -0.4521    9
                             2.1214    A <---- D_N
          f_N/f ---------> 13.5882     B
                            10.0860    C <---------- RE_N/RE
                             1.0336    D
[A_F b]/V_os --------------> 1.5332    E
                           991.4751    I

                             0.8350    0    Print out of Regis-
                             3.1448    1    ters 10-19
                             0.0001    2
                             0.0813    3
                            -0.3264    4
                             3.5207    5
                             0.5965    6
                            -0.3960    7
                            -1.0000    8
                             0.5290    9
Value of RE_N being
evaluated     ---------> 10000.0000
                       3.743772534+10 <------- P_e/Vos
P_s/V_os ------------> 1.370584009+10
                           320.2228 <--------- NTU_e/V_os
NTU_s/V_os ----------->     52.9601

                         20000.0000
                       2.502842147+11
                       9.564330240+10
                           507.5132
                            80.4954
```

APPENDIX II

The purpose of this appendix is to present:

1. (1) A full description of the geometry of each surface evaluated in this study.

2. (2) Friction factor (f) and Colburn Modulus (j) as a funtion of Reynolds number (RE) for each surface evaluated in this study.

3. (3) A complete compilation of the surface performance parameters required to compare each surface evaluated in this study.

FINNED CIRCULAR TUBES
SURFACE CF - 7.34

Tube outside diameter - 0.38 in.
Fin pitch - 7.34 per inch
Flow passage hydraulic diameter - $4r_h$=0.0154 ft.
Fin thickness (average)* - 0.018 in.
Free-flow area/frontal area - σ =0.538
Heat transfer area/total volume - α =140 ft.^{2}/ft.^{3}
Fin area/total area - 0.892

Note: Experimental uncertainty for heat transfer results possibly somewhat greater than the nominal ±5% quoted for the other surfaces because of the necessity of estimating a contact resistance in the bi-metal tubes.

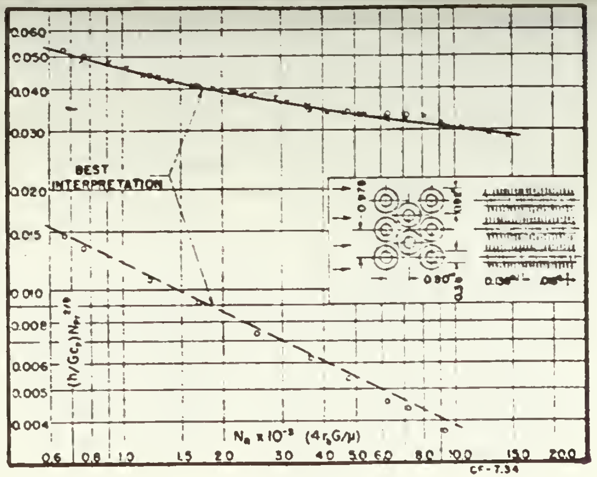
* - Fins slightly tapered.

D_N = 1.5949

$\frac{RE_N}{RE}$ = 7.6227

$\frac{f_N}{f}$ = 11.0631

$\frac{A_F b}{V_{os}}$ = 1.4282



N_R	$N_{St}N_{Pr}^{2/3}$	f
15,000	-	-
12,000	-	-
10,000	0.00388	0.0304
8,000	0.00465	0.0313
6,000	0.00500	0.0326
5,000	0.00547	0.0334
4,000	0.00609	0.0348
3,000	0.00701	0.0365
2,500	0.00770	0.0379
2,000	0.00860	0.0395
1,500	0.00990	0.0420
1,200	0.01105	0.0441
1,000	0.01210	0.0461

Heat Transfer and

Friction Data

FIG 92

APPENDIX I PROGRAM CONSTANTS						REYNOLDS NUMBER $[RE]_N$	$\frac{NTU_e}{V_{os}} = \frac{j_N RE_N A_F b}{D_N^2 V_{os}}$	$\frac{NTU_s}{V_{os}} = \frac{j_s RE\ A_F b}{D_N^2 V_{os}}$	$\frac{P_e}{V_{os}} = \frac{f_N RE_N^3 A_F b}{D_N^4 V_{os}}$	$\frac{P_s}{V_{os}} = \frac{f_s RE^3 A_F b}{D_N^4 V_{os}}$
0	RE	0.0000	10	A_δ/A_T	0.8420	10000	499.98	87.05	1.07 EE 11	3.48 EE 10
1	$A_{f(e)}$	0.1781	11	ℓ	0.2700	20000	710.83	132.31	7.47 EE 11	2.61 EE 11
2	$B_{f(e)}$	-0.1954	12	¶^{1}	1.17 EE -04	30000	871.99	169.02	2.33 EE 12	8.48 EE 11
3	$A_{f(s)}$	0.3752	13	$A_{j(e)}$	0.3311	40000	1007.21	210.10	5.22 EE 12	1.96 EE 12
4	$B_{f(s)}$	-0.0941	14	$B_{j(e)}$	-0.4804	50000	1125.77	230.11	9.76 EE 12	3.74 EE 12
5	D_{2h}	0.1848	15	δ	0.0180	60000	1232.45	256.90	1.63 EE 13	6.35 EE 12
6	Δ_1	-0.00259	16	$A_{j(s)}$	0.5949	70000	1330.10	281.97	2.51 EE 13	9.95 EE 12
7	Δ_2	-0.00835	17	$B_{j(s)}$	-0.3960	80000	1420.60	305.65	3.65 EE 13	1.47 EE 13
8	Δ_3	-0.02426	18	Fin ID	0.0000	90000	1505.23	328.18	5.07 EE 13	2.06 EE 13
9	Δ_4	-0.45208	19	ρ	0.4130	100000	1584.95	349.76	6.82 EE 13	2.80 EE 13
A	Data ID	92.0000	D	X_L	2.1053	110000	1660.47	370.47	8.91 EE 13	3.70 EE 13
B	β	11.6666	E	X_T	2.5658	120000	1732.35	390.46	1.14 EE 14	4.76 EE 13
C	D_o	0.3800	I	Incr'mt	10000	130000	-------	------	-----------	----------
							[1/in^2]	[1/in^2]	[1/in^4]	[1/in^4]

[1] Assumes Aluminum Fin Material & Air @ 90°F

FINNED CIRCULAR TUBES
SURFACE CF - 8.72

Tube outside diameter - 0.38 in.
Fin pitch - 8.72 per inch
Flow passage hydraulic diameter - $4r_h$=0.01288 ft.
Fin thickness (average)* - 0.018 in.
Free-flow area/frontal area - σ =0.524
Heat transfer area/total volume - α =163 ft.^{2}/ft.^{3}
Fin area total area - 0.910

Note: Experimental uncertainty for heat transfer results possibly somewhat greater than the nominal ±5% quoted for the other surfaces because of the necessity of estimating a contact resistance in the bi-metal tubes.

* - Fins slightly tapered.

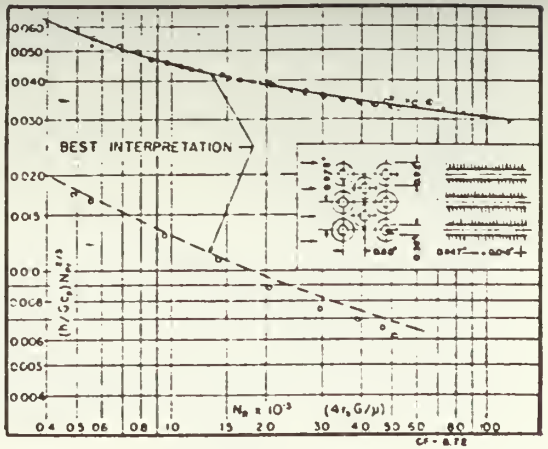


FIG. 93

N_R	$N_{St}N_{Pr}^{2/3}$	f
15,000	-	-
12,000	-	-
10,000	-	0.0306
8,000	-	0.0314
6,000	0.00645	0.0326
5,000	0.00685	0.0333
4,000	0.00740	0.0344
3,000	0.00820	0.0360
2,500	0.00880	0.0371
2,000	0.00960	0.0388
1,500	0.0108	0.0412
1,200	0.0119	0.0433
1,000	0.0129	0.0453

Heat Transfer and Friction Data

D_N = 1.5949

$\frac{RE_N}{RE}$ = 8.8750

$\frac{f_N}{f}$ = 13.9500

$\frac{A_F b}{V_{os}}$ = 1.4282

APPENDIX I PROGRAM CONSTANTS						REYNOLDS NUMBER $[RE]_N$	$\frac{NTU_e}{V_{os}} = \frac{j_N RE_N A_F b}{D_N^2 V_{os}}$	$\frac{NTU_s}{V_{os}} = \frac{j_s RE A_F b}{D_N^2 V_{os}}$	$\frac{P_e}{V_{os}} = \frac{f_N RE_N^3 A_F b}{D_N^4 V_{os}}$	$\frac{P_s}{V_{os}} = \frac{f_s RE^3 A_F b}{D_N^4 V_{os}}$
0	RE	0.0000	10	A_δ/A_T	0.9100	10000	702.75	87.05	1.39 EE 11	3.48 EE 10
1	$A_{f(e)}$	0.1862	11	ℓ	0.2700	20000	1042.73	132.31	9.67 EE 11	2.61 EE 11
2	$B_{f(e)}$	-0.2016	12	τ[1]	1.17 EE -04	30000	1310.10	169.02	3.00 EE 12	8.48 EE 11
3	$A_{f(s)}$	0.3752	13	$A_{j(e)}$	0.2262	40000	1538.22	201.10	6.73 EE 12	1.96 EE 12
4	$B_{f(s)}$	-0.0941	14	$B_{j(e)}$	-0.4127	50000	1740.51	230.10	1.26 EE 13	3.74 EE 12
5	D_{2h}	0.1546	15	δ	0.0180	60000	1924.06	256.90	2.09 EE 13	6.35 EE 12
6	Δ_1	-0.00259	16	$A_{j(s)}$	0.5949	70000	2093.17	281.97	3.22 EE 13	9.95 EE 12
7	Δ_2	-0.00835	17	$B_{j(s)}$	-0.3960	80000	2250.69	305.65	4.68 EE 13	1.47 EE 13
8	Δ_3	-0.02426	18	Fin ID	0.0000	90000	2398.61	328.18	6.51 EE 13	2.06 EE 13
9	Δ_4	-0.45203	19	ρ	0.4130	100000	2538.42	349.75	8.74 EE 13	2.80 EE 13
A	Data ID	93.0000	D	X_L	2.1053	110000	2671.27	370.47	1.14 EE 14	3.70 EE 13
B	β	13.5833	E	X_T	2.5658	120000	2798.01	390.46	1.46 EE 14	4.76 EE 13
C	D_o	0.380	I	Incr'mt	10000	130000	2919.37	409.81	1.82 EE 14	6.01 EE 13
							[1/in^2]	[1/in^2]	[1/in^4]	[i/in^4]

[1] Assumes Aluminum Fin Material & Air @ 90°F

FINNED CIRCULAR TUBES
SURFACE CF - 8.72(c)

Tube outside diameter - 0.42 in.
Fin pitch - 8.72 per inch
Flow passage hydraulic diameter - $4r_h$=0.01452 ft.
Fin thickness (average)* - 0.019 in.
Free-flow area/frontal area - σ =0.494
Heat transfer area/total volume - α =136 ft.^{2}/ft.^{3}
Fin area/total area - 0.876

* - Fins slightly tapered

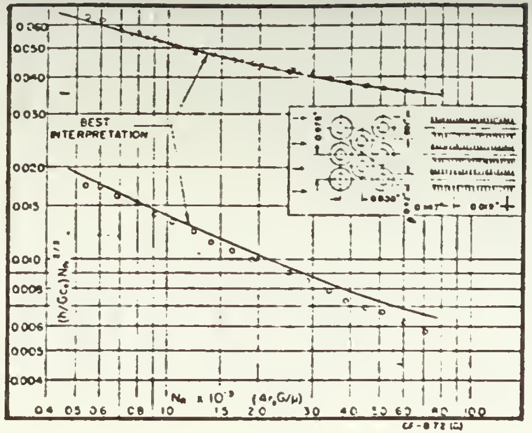


FIG. 94

N_R	$N_{St}N_{Pr}^{2/3}$	f
15,000	-	-
12,000	-	-
10,000	-	-
8,000	0.00638	0.0347
6,000	0.00685	0.0359
5,000	0.00727	0.0368
4,000	0.00765	0.0381
3,000	0.00879	0.0401
2,500	0.00945	0.0418
2,000	0.01035	0.0440
1,500	0.01170	0.0470
1,200	0.01285	0.0495
1,000	0.01390	0.0520

Heat Transfer and

Friction Data

D_N = 1.3460

$\frac{f_N}{f}$ = 10.2703

$\frac{RE_N}{RE}$ = 6.6997

$\frac{A_F b}{V_{os}}$ = 1.3844

APPENDIX I PROGRAM CONSTANTS						REYNOLDS NUMBER $[RE]_N$	$\frac{NTU_e}{V_{os}} = \frac{j_N RE_N A_F b}{D_N^2 V_{os}}$	$\frac{NTU_s}{V_{os}} = \frac{j_s RE\ A_F b}{D_N^2 V_{os}}$	$\frac{P_e}{V_{os}} = \frac{f_N RE_N^3\ A_F b}{D_N^4 V_{os}}$	$\frac{P_s}{V_{os}} = \frac{f_s RE^3 A_F b}{D_N^4 V_{os}}$
0	RE	0.0000	10	A_δ/A_T	0.8760	10000	694.67	106.46	2.07 EE 11	5.65 EE 10
1	$A_{f(e)}$	0.2377	11	ℓ	0.2205	20000	1045.96	161.81	1.43 EE 12	4.25 EE 11
2	$B_{f(e)}$	-0.2192	12	ς^1	6.23 EE -05	30000	1327.51	206.71	4.40 EE 12	1.39 EE 12
3	$A_{f(s)}$	0.3053	13	$A_{j(e)}$	0.2254	40000	1571.18	245.94	9.80 EE 12	3.19 EE 12
4	$B_{f(s)}$	-0.0895	14	$B_{j(e)}$	-0.4027	50000	1789.86	281.43	1.82 EE 13	6.11 EE 12
5	D_{2h}	0.1742	15	δ	0.0190	60000	1990.36	314.19	3.03 EE 13	1.04 EE 13
6	Δ_1	-0.00259	16	$A_{j(s)}$	0.5346	70000	2176.79	344.85	4.65 EE 13	1.63 EE 13
7	Δ_2	-0.00835	17	$B_{j(s)}$	-0.3960	80000	2351.91	373.81	6.73 EE 13	2.40 EE 13
8	Δ_3	-0.02426	18	Fin ID	0.0000	90000	2517.64	401.37	9.34 EE 13	3.39 EE 13
9	Δ_4	-0.45208	19	ρ	0.4878	100000	2675.42	427.75	1.25 EE 14	4.60 EE 13
A	Data ID	94.0000	D	X_L	1.9048	110000	2826.33	453.09	1.63 EE 14	6.07 EE 13
B	β	11.3333	E	X_T	2.3214	120000	2971.22	477.54	2.08 EE 14	7.82 EE 13
C	D_o	0.420	I	Incr'mt	10000	130000	3110.80	501.20	2.60 EE 14	9.87 EE 13
							$[1/in^2]$	$[1/in^2]$	$[1/in^4]$	$[1/in^4]$

[1] Assumes Copper Fin Material & Air @ 90°F

FINNED CIRCULAR TUBES
SURFACE CF-7.0 - 5/8J
(Data of Jameson)

Tube outside diameter - 0.645 in.
Fin pitch - 7.0 per inch
Flow passage hydraulic diameter - $4r_h = 0.0219$ ft.
Fin thickness - 0.010 in.
Free-flow area/frontal area - $\sigma = 0.449$
Heat transfer area/total volume - $\alpha = 82$ ft.^{2}/ft.^{3}
Fin area/total area - 0.830

Note: Minimum free-flow area is in spaces transverse to flow.
These data are included in this compilation because they include compact arrangements of interest that are not adequately covered by Figs. 92 - 95.

D_N = 1.5643

$\frac{RE_N}{RE}$ = 5.6088

$\frac{f_N}{f}$ = 6.7043

$\frac{A_F b}{V_{os}}$ = 1.1859

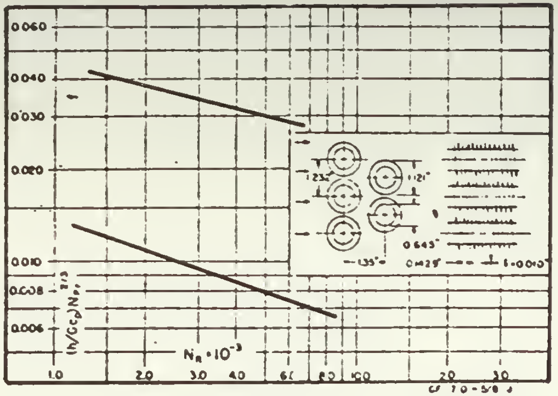


FIG. 96

NOT

AVAILABLE

Heat Transfer and

Friction Data

APPENDIX I PROGRAM CONSTANTS						REYNOLDS NUMBER $[RE]_N$	$\frac{NTU_e}{V_{cs}} = \frac{j_N RE_N A_F b}{D_N^2 V_{os}}$	$\frac{NTU_s}{V_{os}} = \frac{j_s RE\ A_F b}{D_N^2 V_{cs}}$	$\frac{P_e}{V_{cs}} = \frac{f_N RE_N^3 A_F b}{D_N^4 V_{os}}$	$\frac{P_s}{V_{os}} = \frac{f_s RE^3 A_F b}{D_N^4 V_{cs}}$
0	RE	0.0000	10	A_f/A_T	0.8300	10000	319.65	57.62	5.17 EE 10	2.12 EE 10
1	$A_{f(e)}$	0.2646	11	ℓ	0.2380	20000	499.24	87.59	3.47 EE 11	1.57 EE 11
2	$B_{f(e)}$	-0.2559	12	¶[1]	6.23 EE -5	30000	646.39	111.88	1.05 EE 12	5.09 EE 11
3	$A_{f(s)}$	0.2801	13	$A_{j(e)}$	0.1461	40000	775.28	133.11	2.32 EE 12	1.17 EE 12
4	$B_{f(s)}$	-0.1046	14	$B_{j(e)}$	-0.3418	50000	891.80	152.32	4.23 EE 12	2.24 EE 12
5	D_{2h}	0.2628	15	δ	0.0100	60000	999.14	170.05	7.06 EE 12	3.79 EE 12
6	Δ_1	-0.00259	16	$A_{j(s)}$	0.4562	70000	1099.28	186.64	1.08 EE 13	5.92 EE 12
7	Δ_2	-0.00335	17	$B_{j(s)}$	-0.3960	80000	1193.53	202.32	1.55 EE 13	8.72 EE 12
8	Δ_3	-0.02426	18	Fin ID	-1.0000	90000	1282.85	217.24	2.15 EE 13	1.23 EE 13
9	Δ_4	-0.45203	19	ρ	0.5740	100000	1367.94	231.51	2.87 EE 13	1.66 EE 13
A	Data ID	96.0000	D	X_L	2.0930	110000	-------	-------	----------	----------
B	β	6.8333	E	X_T	1.9101	120000	-------	--------	----------	----------
C	D_o	0.6450	I	Incr'mt	10000	130000	-------	--------	----------	----------
							[1/in^2]	[1/in^2]	[1/in^4]	[1/in^4]

[1] Assumes Copper Fin Material & Air @ 90°F

FINNED CIRCULAR TUBES
SURFACES CF - 8.7 - 5/8J
(Data of Jameson)

Tube outside diameter - 0.645 in.
Fin pitch - 8.7 per inch
Fin thickness - 0.010 in.
Fin area/total area - 0.862

	A	B
Flow passage hydraulic diameter - $4r_h$ =	0.01797	0.0383 ft.
Free-flow area/frontal area - σ =	0.443	0.628
Heat transfer area/total volume - α =	98.7	65.7 $ft.^2/ft.^3$

Note: Minimum free-flow area is in spaces transverse to flow. These data are included in this compilation because they include compact arrangements of interest that are not adequately covered by Figs. 92 - 98.

D_N = 1.5643

$\frac{RE_N}{RE}$ = 6.7510

$\frac{f_N}{f}$ = 8.3760

$\frac{A_F b}{V_{os}}$ = 1.1859

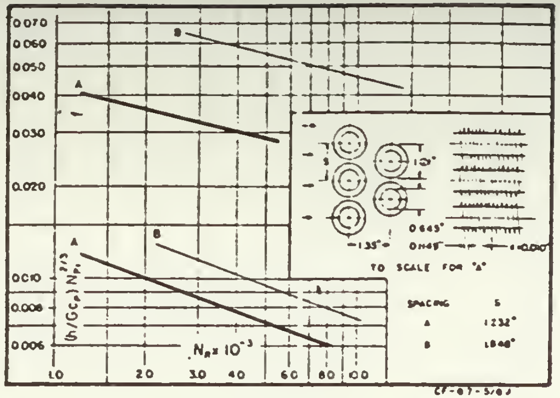


FIG. 97 A

NOT

AVAILABLE

Heat Transfer and

Friction Data

APPENDIX I PROGRAM CONSTANTS						REYNOLDS NUMBER $[RE]_N$	$\frac{NTU_e}{V_{os}} = \frac{j_N RE_N A_F b}{D_N^2 V_{os}}$	$\frac{NTU_s}{V_{os}} = \frac{j_s RE\ A_F b}{D_N^2 V_{os}}$	$\frac{P_e}{V_{os}} = \frac{f_N RE_N^3 A_F b}{D_N^4 V_{os}}$	$\frac{P_s}{V_{os}} = \frac{f_s RE^3 A_F b}{D_N^4 V_{os}}$
0	RE	0.0000	10	A_j/A_T	0.8620	10000	384.52	57.62	6.41 EE 10	2.12 EE 10
1	$A_{f(e)}$	0.2319	11	ℓ	0.2390	20000	593.20	87.58	4.33 EE 11	1.57 EE 11
2	$B_{f(e)}$	-0.2454	12	q^1	6.23 EE -05	30000	762.57	111.88	1.32 EE 12	5.09 EE 11
3	$A_{f(s)}$	0.2801	13	$A_{j(e)}$	0.1541	40000	910.03	133.11	2.92 EE 12	1.17 EE 12
4	$B_{f(s)}$	-0.1046	14	$B_{j(e)}$	-0.3596	50000	1042.76	152.32	5.40 EE 12	2.24 EE 12
5	D_{2h}	0.2156	15	δ	0.0100	60000	1164.62	170.05	8.93 EE 12	3.79 EE 12
6	Δ_1	-0.00259	16	$A_{j(s)}$	0.4562	70000	1277.98	186.64	1.36 EE 13	5.92 EE 12
7	Δ_2	-0.00835	17	$B_{j(s)}$	-0.3960	80000	1384.42	202.32	1.97 EE 13	8.72 EE 12
8	Δ_3	-0.02426	18	Fin ID	-1.0000	90000	1485.09	217.24	2.73 EE 13	1.23 EE 13
9	Δ_4	-0.45208	19	ρ	0.5740	100000	1580.82	231.51	3.65 EE 13	1.66 EE 13
A	Data ID	97.1000	D	X_L	2.0930	110000	1672.27	245.23	4.74 EE 13	2.19 EE 13
B	β	8.225	E	X_T	1.9101	120000	-------	------	----------	----------
C	D_o	0.6450	I	Incr'mt	10000	130000	-------	------	----------	----------
							$[1/in^2]$	$[1/in^2]$	$[1/in^4]$	$[1/in^4]$

---

[1] Assumes Copper Fin Material & Air @ 90°F

FINNED CIRCULAR TUBES
SURFACES CF - 8.7 - 5/8J
(Data of Jameson)

Tube outside diameter – 0.645 in.
Fin pitch – 8.7 per inch
Fin thickness – 0.010 in.
Fin area total area – 0.862

		A	B
Flow passage hydraulic diameter –	$4r_h$ =	0.01797	0.0383 ft.
Free-flow area/frontal area –	σ =	0.443	0.628
Heat transfer area/total volume –	α =	98.7	65.7 $ft.^2/ft.^3$

Note: Minimum free-flow area is in spaces transverse to flow. These data are included in this compilation because they include compact arrangements of interest that are not adequately covered by Figs. 92 - 96.

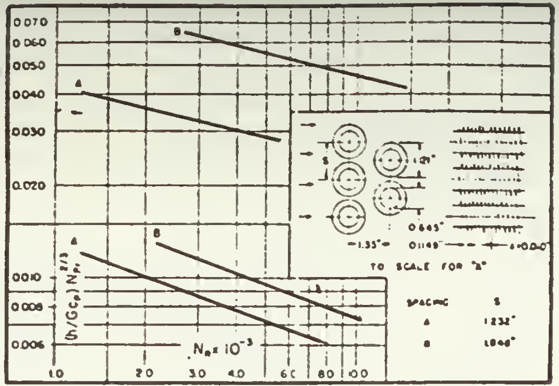


FIG. 97 B

NOT

AVAILABLE

Heat Transfer and

Friction Data

D_N = 3.2059

$\frac{f_N}{f}$ = 7.4695

$\frac{RE_N}{RE}$ = 6.7408

$\frac{A_F b}{V_{os}}$ = 1.4982

APPENDIX I PROGRAM CONSTANTS

0	RE	0.0000	10	A_f/A_T	0.8620
1	$A_{f(e)}$	0.5416	11	ℓ	0.2380
2	$B_{f(e)}$	-0.2676	12	¶[1]	6.23 EE -05
3	$A_{f(s)}$	0.4639	13	$A_{j(e)}$	0.2163
4	$B_{f(s)}$	-0.1046	14	$B_{j(e)}$	-0.3666
5	D_{2h}	0.4596	15	δ	0.0100
6	Δ_1	-0.00259	16	$A_{j(s)}$	0.6485
7	Δ_2	-0.00835	17	$B_{j(s)}$	-0.3960
8	Δ_3	-0.02426	18	Fin ID	-1.0000
9	Δ_4	-0.45208	19	ρ	0.5754
A	Data ID	97.2000	D	X_L	2.0930
B	β	5.475	E	X_T	2.8651
C	D_o	0.6450	I	Incr'mt	10000

REYNOLDS NUMBER $(RE)_N$	$\frac{NTU_e}{V_{os}} = \frac{j_N RE_N A_F b}{D_N^2 V_{os}}$	$\frac{NTU_s}{V_{os}} = \frac{j_s RE\ A_F b}{D_N^2 V_{os}}$	$\frac{P_e}{V_{os}} = \frac{f_N RE_N^3\ A_F b}{D_N^4 V_{os}}$	$\frac{P_s}{V_{os}} = \frac{f_s RE^3 A_F b}{D_N^4 V_{os}}$
10000	149.17	24.64	8.13 EE 09	2.51 EE 09
20000	229.90	37.45	5.40 EE 10	1.87 EE 10
30000	295.64	47.84	1.64 EE 11	6.04 EE 10
40000	353.08	56.91	3.59 EE 11	1.39 EE 11
50000	404.97	65.13	6.60 EE 11	2.65 EE 11
60000	452.76	72.71	1.09 EE 12	4.50 EE 11
70000	497.38	79.80	1.66 EE 12	7.03 EE 11
80000	539.40	86.51	2.39 EE 12	1.03 EE 12
90000	579.27	92.88	3.29 EE 12	1.45 EE 12
100000	617.30	98.99	4.39 EE 12	1.97 EE 12
110000	653.73	104.85	5.69 EE 12	2.60 EE 12
120000	688.76	110.51	7.22 EE 12	3.35 EE 12
130000	722.54	115.98	8.99 EE 12	4.22 EE 12
	$[1/in^2]$	$[1/in^2]$	$[1/in^4]$	$[1/in^4]$

[1] Assumes Copper Fin Material & Air @ 90°F

FINNED CIRCULAR TUBES
SURFACES CF - 9.05-3/4J
(Data of Jameson)
Tube outside diameter - 0.774 in.
Fin pitch - 9.05 per inch
Fin thickness - 0.012 in.
Fin area/total area - 0.835

	A	B
Flow passage hydraulic diameter - $4r_h$ =	0.01681	0.02685
Free-flow area/frontal area - σ =	0.455	0.572
Heat transfer area/total volume - α =	108	85.1

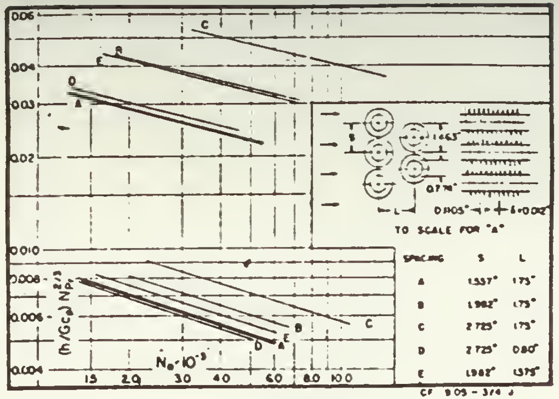


FIG. 98 A

NOT

AVAILABLE

Heat Transfer and

Friction Data

D_N = 2.2541

$\frac{f_N}{f}$ = 13.7185

$\frac{RE_N}{RE}$ = 10.0851

$\frac{A_F b}{V_{os}}$ = 1.2157

APPENDIX I PROGRAM CONSTANTS						REYNOLDS NUMBER $[RE]_N$	$\frac{NTU_e}{V_{cs}} = \frac{j_N RE_N A_F b}{D_N^2 V_{os}}$	$\frac{NTU_s}{V_{os}} = \frac{j_s RE A_F b}{D_N^2 V_{os}}$	$\frac{P_e}{V_{os}} = \frac{f_N RE_N^3 A_F b}{D_N^4 V_{os}}$	$\frac{P_s}{V_{os}} = \frac{f_s RE^3 A_F b}{D_N^4 V_{os}}$
0	RE	0.0000	10	A_f/A_T	0.8350	10000	230.42	30.46	2.26 EE 10	5.64 EE 09
1	$A_{f(e)}$	0.2263	11	ℓ	0.3445	20000	363.32	46.29	1.50 EE 11	4.24 EE 10
2	$B_{f(e)}$	-0.2707	12	¶[1]	6.23 EE -05	30000	472.95	59.14	4.53 EE 11	1.38 EE 11
3	$A_{f(s)}$	0.2753	13	$A_{j(e)}$	0.0342	40000	569.34	70.36	9.93 EE 11	3.18 EE 11
4	$B_{f(s)}$	-0.0904	14	$B_{j(e)}$	-0.3273	50000	656.71	80.51	1.83 EE 12	6.10 EE 11
5	D_{2h}	0.2017	15	δ	0.0120	60000	737.36	89.89	3.00 EE 12	1.04 EE 12
6	Δ_1	-0.00259	16	$A_{j(s)}$	0.4884	70000	812.71	98.66	4.57 EE 12	1.62 EE 12
7	Δ_2	-0.00835	17	$B_{j(s)}$	-0.3960	80000	883.70	106,94	6.58 EE 12	2.39 EE 12
8	Δ_3	-0.02426	18	Fin ID	-1.0000	90000	951.05	114.83	9.08 EE 12	3.37 EE 12
9	Δ_4	-0.45208	19	ρ	0.5290	100000	1015.25	122.37	1.21 EE 13	4.58 EE 12
A	Data ID	98.10000	D	X_L	2.2610	110000	1076.71	129.62	1.57 EE 13	6.04 EE 12
B	β	9.0000	E	X_T	2.0116	120000	1135.74	136.62	1.99 EE 13	7.79 EE 12
C	D_o	0.7740	I	Incr'mt	10000	130000	1192.60	143.39	2.48 EE 13	9.83 EE 12
							$[1/in^2]$	$[1/in^2]$	$[1/in^4]$	$[1/in^4]$

[1] Assumes Copper Fin Material & Air @ 90°F

FINNED CIRCULAR TUBES
SURFACES CF - 9.05-3/4J
(Data of Jameson)
Tube outside diameter - 0.774 in.
Fin pitch - 9.05 per inch
Fin thickness - 0.012 in.
Fin area/total area - 0.835

	A	B
Flow passage hydraulic diameter - $4r_h$ =	0.01681	0.02685
Free-flow area/frontal area - σ =	0.455	0.572
Heat transfer area/total volume - α =	108	85.1

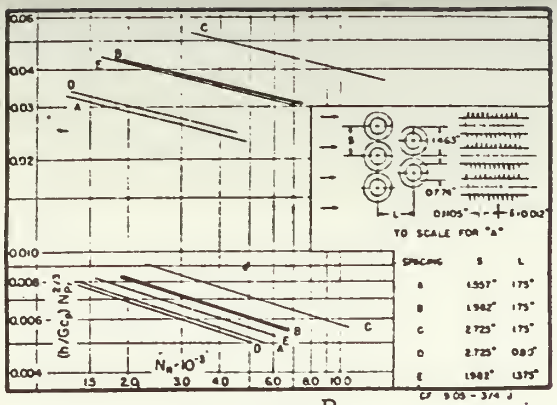


FIG. 98 B

NOT

AVAILABLE

Heat Transfer and

Friction Data

D_N = 3.4776

$\frac{f_N}{f}$ = 12.2870

$\frac{RE_N}{RE}$ = 10.1158

$\frac{A_F b}{V_{os}}$ = 1.4103

APPENDIX I PROGRAM CONSTANTS						REYNOLDS NUMBER $[RE]_N$	$\frac{NTU_e}{V_{os}} = \frac{j_N RE_N A_F b}{D_N^2 V_{os}}$	$\frac{NTU_s}{V_{os}} = \frac{j_s RE\ A_F b}{D_N^2 V_{os}}$	$\frac{P_e}{V_{os}} = \frac{f_N RE_N^3 A_F b}{D_N^4 V_{os}}$	$\frac{P_s}{V_{os}} = \frac{f_s RE^3 A_F b}{D_N^4 V_{os}}$
0	RE	0.0000	10	A_δ/A_T	0.8350	10000	125.61	18.35	6.01 EE 09	1.57 EE 09
1	$A_{f(e)}$	0.2905	11	ℓ	0.3445	20000	199.11	27.89	4.03 EE 10	1.18 EE 10
2	$B_{f(e)}$	-0.2531	12	¶[1]	6.23 EE -05	30000	260.17	35.63	1.23 EE 11	3.83 EE 10
3	$A_{f(s)}$	0.3775	13	$A_{j(e)}$	0.0947	40000	314.16	42.39	2.71 EE 11	8.84 EE 10
4	$B_{f(s)}$	-0.0904	14	$B_{j(e)}$	-0.3239	50000	363.35	48.50	5.00 EE 11	1.69 EE 11
5	D_{2h}	0.3222	15	δ	0.0120	60000	408.95	54.15	8.25 EE 11	2.88 EE 11
6	Δ_1	-0.00259	16	$A_{j(s)}$	0.6037	70000	451.73	59.43	1.26 EE 12	4.51 EE 11
7	Δ_2	-0.00835	17	$B_{j(s)}$	-0.3960	80000	492.18	64.43	1.82 EE 12	6.65 EE 11
8	Δ_3	-0.02426	18	Fin ID	-1.0000	90000	530.68	69.18	2.51 EE 12	9.36 EE 11
9	Δ_4	-0.45208	19	o	0.5290	100000	567.51	73.72	3.35 EE 12	1.27 EE 12
A	Data ID	98.2000	D	X_L	2.2610	110000	602.88	78.09	4.36 EE 12	1.68 EE 12
B	β	7.09166	E	X_T	2.5607	120000	636.95	82,30	5.53 EE 12	2.16 EE 12
C	D_o	0.774	I	Incr'mt	10000	130000	669.85	86.38	6.90 EE 12	2.73 EE 12
							$[1/in^2]$	$[1/in^2]$	$[1/in^4]$	$[1/in^4]$

[1] Assumes Copper Fin Material & Air @ 90°F

FINNED CIRCULAR TUBES
SURFACES CF - 9.05-3/4J
(Data of Jameson)
Tube outside diameter - 0.774 in.
Fin pitch - 9.05 per inch
Fin thickness - 0.012 in.
Fin area/total area - 0.838

	C	D	E
Flow passage hydraulic diameter - $4r_h$ =	0.0445	0.01587	0.02108 ft.
Free-flow area/frontal area - σ =	0.688	0.537	0.572
Heat transfer area/total volume - α =	61.9	135	108 ft^2/ft^3

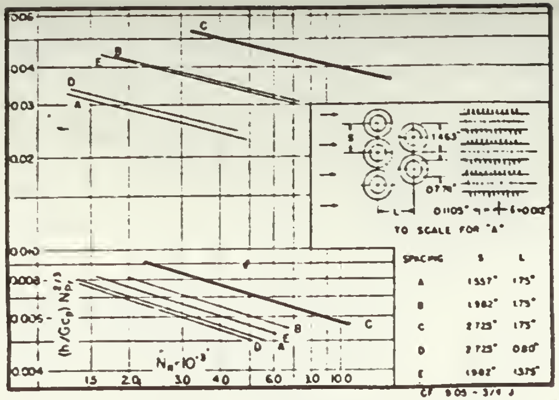


FIG. 9.3 C

NOT

AVAILABLE

Heat Transfer and

Friction Data

D_N = 5.6165

$\frac{f_N}{f}$ = 11.3690

$\frac{RE_N}{RE}$ = 10.1163

$\frac{A_F b}{V_{os}}$ = 1.5887

APPENDIX I PROGRAM CONSTANTS					
0	RE	0.0000	10	A_f/A_T	0.8350
1	$A_{f(e)}$	0.3850	11	ℓ	0.3145
2	$B_{f(e)}$	-0.2462	12	ϕ^1	6.23 EE -05
3	$A_{f(s)}$	0.5232	13	$A_{j(e)}$	0.1023
4	$B_{f(s)}$	-0.0904	14	$B_{j(e)}$	-0.3137
5	D_{2h}	0.5340	15	δ	0.0120
6	Δ_1	-0.00259	16	$A_{j(s)}$	0.7697
7	Δ_2	-0.00835	17	$B_{j(s)}$	-0.3960
8	Δ_3	-0.02426	18	Fin ID	-1.0000
9	Δ_4	-0.45208	19	ρ	0.5290
A	Data ID	98.3000	D	X_L	2.2610
B	β	5.1583	E	X_T	3.5207
C	D_o	0.774	I	Incr'mt	10000

REYNOLDS NUMBER $(RE)_N$	$\frac{NTU_e}{V_{cs}} = \frac{j_N RE_N A_F b}{D_N^2 V_{os}}$	$\frac{NTU_s}{V_{os}} = \frac{j_s RE A_F b}{D_N^2 V_{os}}$	$\frac{P_e}{V_{os}} = \frac{f_N RE_N^3 A_F b}{D_N^4 V_{os}}$	$\frac{P_s}{V_{os}} = \frac{f_s RE^3 A_F b}{D_N^4 V_{os}}$
10000	61.56	10.10	1.28 EE 09	3.63 EE 08
20000	98.49	15.36	8.63 EE 09	2.73 EE 09
30000	129.47	19.62	2.63 EE 10	8.83 EE 09
40000	157.06	23.34	5.82 EE 10	2.05 EE 10
50000	182.33	26.71	1.08 EE 11	3.93 EE 10
60000	205.38	29.81	1.78 EE 11	6.67 EE 10
70000	228.05	32.72	2.72 EE 11	1.05 EE 11
80000	249.11	35.47	3.92 EE 11	1.54 EE 11
90000	269.23	38.09	5.43 EE 11	2.17 EE 11
100000	288.54	40.59	7.25 EE 11	2.95 EE 11
110000	307.13	43.00	9.43 EE 11	3.89 EE 11
120000	325.10	45.32	1.20 EE 12	5.01 EE 11
130000	342.50	47.56	1.49 EE 12	6.33 EE 11
	$[1/in^2]$	$[1/in^2]$	$[1/in^4]$	$[1/in^4]$

[1] Assumes Copper Fin Material & Air @ 90°F

FINNED CIRCULAR TUBES
SURFACES CF - 9.05-3/4J
(Data of Jameson)
Tube outside diameter - 0.774 in.
Fin pitch - 9.05 per inch
Fin thickness - 0.012 in.
Fin area/total area - 0.830

	C	D	E
Flow passage hydraulic diameter - $4r_h$ =	0.0445	0.01367	0.02108 ft.
Free-flow area/frontal area - σ =	0.686	0.627	0.572
Heat transfer area/total volume - α =	61.0	138	108 ft²/ft³

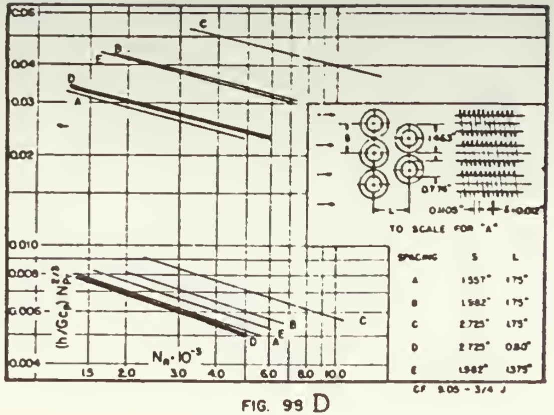


FIG. 99 D

NOT

AVAILABLE

Heat Transfer and

Friction Data

$D_N = \underline{2.1214}$

$\frac{f_N}{f} = \underline{13.5882}$

$\frac{RE_N}{RE} = \underline{10.0860}$

$\frac{A_F b}{V_{os}} = \underline{1.5332}$

NOTE: Minimum free flow area is in diagonals

APPENDIX I PROGRAM CONSTANTS						REYNOLDS NUMBER $[RE]_N$	$\frac{NTU_e}{V_{os}} = \frac{j_N RE_N A_F b}{D_N^2 V_{os}}$	$\frac{NTU_s}{V_{os}} = \frac{j_s RE A_F b}{D_N^2 V_{os}}$	$\frac{P_e}{V_{os}} = \frac{f_N RE_N^3 A_F b}{D_N^4 V_{os}}$	$\frac{P_s}{V_{os}} = \frac{f_s RE^3 A_F b}{D_N^4 V_{os}}$
0	X_D	2.0413	10	A_δ/A_T	0.8350	10000	320.22	52.96	3.74 EE 10	1.37 EE 10
1	$A_{f(e)}$	0.2173	11	$\ell/\sqrt{\delta}$	3.1448	20000	507.51	80.49	2.50 EE 11	9.56 EE 10
2	$B_{f(e)}$	-0.2590	12	¶[1]	6.23 EE -05	30000	663.40	102.83	7.61 EE 11	2.98 EE 11
3	$A_{f(s)}$	1.1125	13	$A_{j(e)}$	0.0813	40000	801.54	122.35	1.67 EE 12	6.67 EE 11
4	$B_{f(s)}$	-0.1971	14	$B_{j(e)}$	-0.3264	50000	927.64	140.40	3.08 EE 12	1.25 EE 12
5	D_{2h}	0.1904	15	X_T	3.5207	60000	1044.81	156.30	5.08 EE 12	2.08 EE 12
6	Δ_1	-0.00239	16	$A_{j(s)}$	0.5965	70000	1154.96	171.55	7.76 EE 12	3.20 EE 12
7	Δ_2	-0.00835	17	$B_{j(s)}$	-0.3960	80000	1259.38	185.96	1.12 EE 13	4.66 EE 12
8	Δ_3	-0.02426	18	Fin ID	-1.0000	90000	1358.98	199.67	1.54 EE 13	6.48 EE 12
9	Δ_4	-0.45208	19	ρ	0.5290	100000	1454.47	212.79	2.06 EE 13	8.71 EE 12
A	Data ID	98.4000	D	X_L	1.03359	110000	1546.37	225.40	2.68 EE 13	1.14 EE 13
B	β	11.2500	Σ	α	59.5804	120000	1635.10	236.56	3.40 EE 13	1.45 EE 13
C	D_o	0.7740	I	Incr'mt	10000	130000	1721.01	249.33	4.23 EE 13	1.82 EE 13
							[1/in²]	[1/in²]	[1/in⁴]	[1/in⁴]

[1] Assumes Copper Fin Material & Air @ 90°F

FINNED CIRCULAR TUBES
SURFACES CF - 9.05-3/4J
(Data of Jameson)
Tube outside diameter - 0.774 in.
Fin pitch - 9.05 per inch
Fin thickness - 0.012 in.
Fin area/total area - 0.838

	C	D	E
Flow passage hydraulic diameter - $4r_h$ =	0.0446	0.01587	0.02108 ft.
Free-flow area/frontal area - σ =	0.688	0.637	0.572
Heat transfer area/total volume - α =	61.9	135	108 $ft.^2/ft.^3$

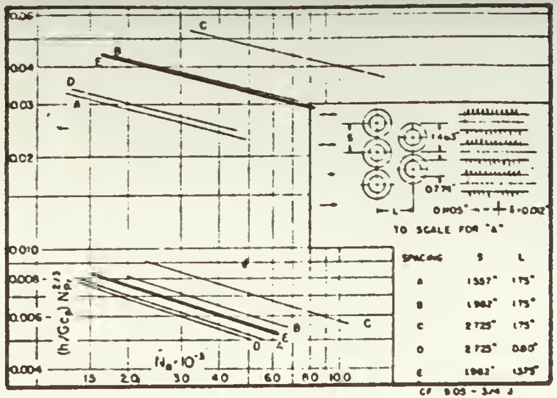


FIG. 98E

NOT

AVAILABLE

Heat Transfer and

Friction Data

D_N = 2.7324

$\frac{f_N}{f}$ = 12.3864

$\frac{RE_N}{RE}$ = 10.0869

$\frac{A_F b}{V_{os}}$ = 1.4733

APPENDIX I PROGRAM CONSTANTS						REYNOLDS NUMBER [RE]n	$\frac{NTU_e}{V_{os}} = \frac{j_N RE_N A_F b}{D_N^2 V_{os}}$	$\frac{NTU_s}{V_{os}} = \frac{j_s RE\ A_F b}{D_N^2 V_{os}}$	$\frac{P_e}{V_{os}} = \frac{f_N RE_N^3\ A_F b}{D_N^4 V_{os}}$	$\frac{P_s}{V_{os}} = \frac{f_s RE^3 A_F b}{D_N^4 V_{os}}$
0	RE	0.0000	10	A_f/A_T	0.8350	10000	198.12	29.38	1.64 EE 10	3.80 EE 09
1	$A_{f(e)}$	0.3020	11	ℓ	0.3445	20000	312.56	44.65	1.09 EE 11	2.77 EE 10
2	$B_{f(e)}$	-0.2607	12	¶[1]	6.23 EE -05	30000	407.15	57.05	3.32 EE 11	9.84 EE 10
3	$A_{f(s)}$	0.4972	13	$A_{j(e)}$	0.0915	40000	490.48	67.87	7.30 EE 11	2.01 EE 11
4	$B_{f(s)}$	-0.1349	14	$B_{j(e)}$	-0.3288	50000	566.15	77.66	1.34 EE 12	3.82 EE 11
5	D_{2h}	0.2530	15	δ	0.0120	60000	636.11	86.71	2.22 EE 12	6.44 EE 11
6	Δ_1	-0.00259	16	$A_{j(s)}$	0.5712	70000	701.57	95.17	3.38 EE 12	1.00 EE 12
7	Δ_2	-0.00835	17	$B_{j(s)}$	-0.3960	80000	763.35	103.16	4.87 EE 12	1.47 EE 12
8	Δ_3	-0.02426	18	Fin ID	-1.0000	90000	822.04	110.77	6.73 EE 12	2.06 EE 12
9	Δ_4	-0.45208	19	ρ	0.5290	100000	878.06	118.04	8.98 EE 12	2.78 EE 12
A	Data ID	98.5000	D	X_L	1.7765	110000	931.76	125.04	1.17 EE 13	3.66 EE 12
B	β	9.0000	E	X_T	2.5607	120000	983.41	131.79	1.48 EE 13	4.79 EE 12
C	D_o	0.774	I	Incr'mt	10000	130000	1033.22	138.31	1.84 EE 13	5.90 EE 12
							$[1/in^2]$	$[1/in^2]$	$[1/in^4]$	$[1/in^4]$

[1] Assumes Copper Fin Material & Air @ 90°F

FINNED CIRCULAR TUBES
SURFACES CF - 8.8 - 1.0J
(Data of Jameson)

Tube outside diameter - 1.024 in.
Fin pitch - 8.8 per inch
Fin thickness - 0.012 in.
Fin area/total area - 0.825

	A	B	
Flow passage hydraulic diameter - $4r_h$ =	0.01927	0.0443	ft.
Free-flow/frontal area - σ =	0.439	0.643	
Heat transfer area/total volume - α =	91.2	58.1	$ft.^2/ft.^3$

Note: Minimum free-flow area is in spaces transverse to flow. These data are included in this compilation because they include compact arrangements of interest that are not adequately covered by Figs. 92 - 95.

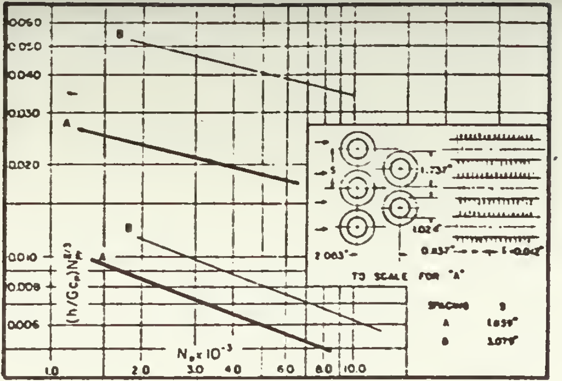


FIG. 99 A

NOT

AVAILABLE

Heat Transfer and

Friction Data

D_N = 2.3984

$\frac{f_N}{f}$ = 12.2399

$\frac{RE_N}{RE}$ = 9.5477

$\frac{A_F b}{V_{os}}$ = 1.1989

APPENDIX I PROGRAM CONSTANTS

0	RE	0.0000	10	A_f/A_T	0.8250
1	$A_{f(e)}$	0.1542	11	ℓ	0.3565
2	$B_{f(e)}$	-0.2473	12	σ^1	6.23 EE -05
3	$A_{f(s)}$	0.2719	13	$A_{j(e)}$	0.1432
4	$B_{f(s)}$	-0.1028	14	$B_{j(e)}$	-0.3727
5	D_{2h}	0.2312	15	δ	0.0120
6	Δ_1	-0.00259	16	$A_{j(s)}$	0.4529
7	Δ_2	-0.00835	17	$B_{j(s)}$	-0.3960
8	Δ_3	-0.02426	18	Fin ID	-1.0000
9	Δ_4	-0.45208	19	ρ	0.5895
A	Data ID	99.100	D	X_L	2.0146
B	β	7.6000	E	X_T	1.9131
C	D_o	1.024	I	Incr'mt	10000

REYNOLDS NUMBER [RE]n	$\frac{NTU_e}{V_{os}} = \frac{j_N RE_N A_F b}{D_N^2 V_{os}}$	$\frac{NTU_s}{V_{os}} = \frac{j_s RE A_F b}{D_N^2 V_{os}}$	$\frac{P_e}{V_{os}} = \frac{f_N RE_N^3 A_F b}{D_N^4 V_{os}}$	$\frac{F_s}{V_{os}} = \frac{f_s RE^3 A_F b}{D_N^4 V_{os}}$
10000	226.75	24.60	1.22 EE 10	3.82 EE 09
20000	346.34	37.39	8.23 EE 10	2.85 EE 10
30000	442.58	47.77	2.51 EE 11	9.22 EE 10
40000	525.90	56.84	5.54 EE 11	2.12 EE 11
50000	600.59	65.04	1.02 EE 12	4.05 EE 11
60000	668.92	72.61	1.69 EE 12	6.87 EE 11
70000	732.30	79.69	2.59 EE 12	1.07 EE 12
80000	791.67	86.39	3.73 EE 12	1.58 EE 12
90000	847.70	92.76	5.16 EE 12	2.22 EE 12
100000	900.88	98.85	6.90 EE 12	3.02 EE 12
110000	951.59	104.71	8.97 EE 12	3.98 EE 12
120000	1000.13	110.36	1.14 EE 13	5.12 EE 12
130000	1046.74	115.82	1.42 EE 13	6.45 EE 12
	[1/in^2]	[1/in^2]	[1/in^4]	[1/in^4]

---

[1] Assumes Copper Fin Material & Air @ 90°F

FINNED CIRCULAR TUBES
SURFACES CF - 8.8 - 1.0J
(Data of Jameson)
Tube outside diameter - 1.024 in.
Fin pitch - 8.8 per inch
Fin thickness - 0.012 in.
Fin area/total area - 0.825

	A	B	
Flow passage hydraulic diameter - $4r_h$ =	0.01927	0.0443	ft.
Free-flow/frontal area - σ =	0.439	0.643	
Heat transfer area/total volume - α =	91.2	58.1	$ft.^2/ft.^3$

Note: Minimum free-flow area is in spaces transverse to flow. These data are included in this compilation because they include compact arrangements of interest that are not adequately covered by Figs. 92 - 95.

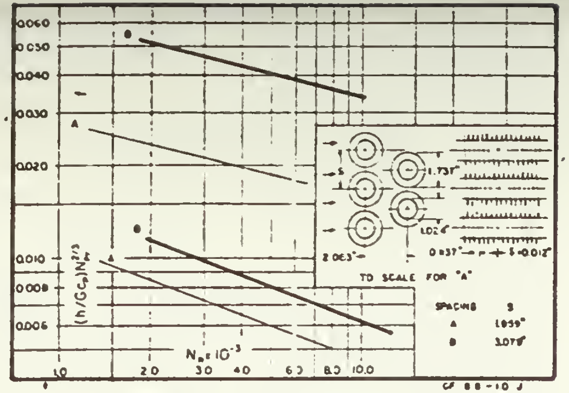


FIG 39 B

NOT

AVAILABLE

Heat Transfer and

Friction Data

D_N = 5.2713

$\frac{f_N}{f}$ = 10.6684

$\frac{RE_N}{RE}$ = 9.5599

$\frac{A_F b}{V_{os}}$ = 1.534

APPENDIX I PROGRAM CONSTANTS						REYNOLDS NUMBER $[RE]_n$	$\frac{NTU_e}{V_{os}} = \frac{j_N RE_N A_F b}{D_N^2 V_{os}}$	$\frac{NTU_s}{V_{os}} = \frac{j_s RE A_F b}{D_N^2 V_{os}}$	$\frac{P_e}{V_{os}} = \frac{f_N RE_N^3 A_F b}{D_N^4 V_{os}}$	$\frac{P_s}{V_{os}} = \frac{f_s RE^3 A_F b}{D_N^4 V_{os}}$
0	RE	0.0000	10	A_f/A_T	0.8250	10000	78.61	9.60	1.23 EE 09	3.65 EE 08
1	$A_{f(e)}$	0.3599	11	ℓ	0.3565	20000	120.12	14.59	8.60 EE 09	2.72 EE 09
2	$B_{f(e)}$	-0.2563	12	¶[1]	6.23 EE -05	30000	153.70	18.63	2.62 EE 10	8.80 EE 09
3	$A_{f(s)}$	0.4730	13	$A_{j(e)}$	0.2027	40000	182.91	22.17	5.76 EE 10	2.02 EE 10
4	$B_{f(s)}$	-0.1027	14	$B_{j(e)}$	-0.3787	50000	209.22	25.37	1.06 EE 11	3.86 EE 10
5	D_{2h}	0.5316	15	δ	0.0120	60000	233.39	28.32	1.75 EE 11	6.55 EE 10
6	Δ_1	-0.00259	16	$A_{j(s)}$	0.6671	70000	255.90	31.08	2.67 EE 11	1.02 EE 11
7	Δ_2	-0.00835	17	$B_{j(s)}$	-0.3960	80000	277.07	33.70	3.86 EE 11	1.51 EE 11
8	Δ_3	-0.02426	18	Fin ID	-1.0000	90000	297.13	36.18	5.33 EE 11	2.12 EE 11
9	Δ_4	-0.45208	19	ρ	0.5995	100000	316.23	38.56	7.11 EE 11	2.88 EE 11
A	Data ID	99.200	D	X_L	2.0146	110000	334.50	40.84	9.24 EE 11	3.79 EE 11
B	β	4.9416	E	X_T	3.0068	120000	352.06	43.05	1.17 EE 12	4.38 EE 11
C	D_o	1.024	I	Incr'mt	10000	130000	368.97	45.18	1.46 EE 12	6.16 EE 11
							$[1/in^2]$	$[1/in^2]$	$[1/in^4]$	$[1/in^4]$

[1] Assumes Copper Fin Material & Air @ 90°F

FINNED CIRCULAR TUBES
SURFACE 8.0 - 3/8 T
(Data of Trane Co.)

Tube outside diameter - 0.402 in.
Fin pitch - 8.0 per inch
Flow passage hydraulic diameter - $4r_h$=0.01192 ft.
Fin thickness - 0.013 in.
Free-flow area/frontal area - σ =0.534
Heat transfer area/total volume - α =179 ft.^{2}/ft.^{3}
Fin area/total area - 0.839

Note: Minimum free-flow area in spaces transverse to flow.
These data are included in this compilation because they apply to a compact surface configuration of considerable technical interest for which no data have been obtained on this project.

D_N = 1.6402

$\frac{f_N}{f}$ = 14.4115

$\frac{RE_N}{RE}$ = 10.2285

$\frac{A_F b}{V_{os}}$ = 1.4014

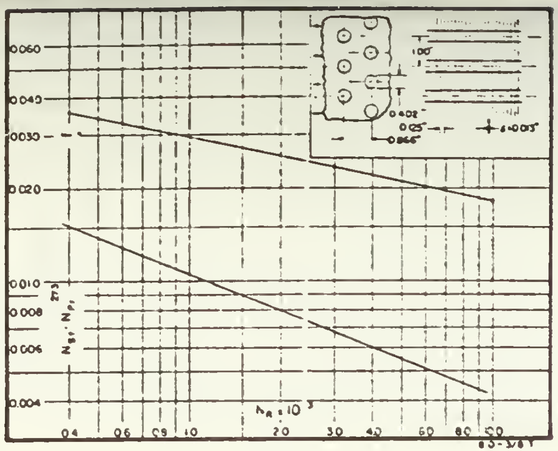


FIG 100

NOT

AVAILABLE

Heat Transfer and

Friction Data

APPENDIX I PROGRAM CONSTANTS					
0	RE	0.00	10	A_δ/A_T	0.8390
1	$A_{f(e)}$	0.1223	11	ℓ	0.3240
2	$B_{f(e)}$	-0.2073	12	q'	1.2 EE -04
3	$A_{f(s)}$	0.3514	13	$A_{j(e)}$	0.1650
4	$B_{f(s)}$	-0.0896	14	$B_{j(e)}$	-0.3986
5	D_{2h}	0.1430	15	δ	0.0130
6	Δ_1	-0.00259	16	$A_{j(s)}$	0.5830
7	Δ_2	-0.00835	17	$B_{j(s)}$	-0.3960
8	Δ_3	-0.02426	18	Fin ID	-1.0000
9	Δ_4	-0.45209	19	ρ	0.3829
A	Data ID	100.00	D	X_L	2.1542
B	β	14.9166	E	X_T	2.4876
C	D_o	0.402	I	Incr'mt	10000

REYNOLDS NUMBER $[RE]_N$	$\frac{NTU_e}{V_{cs}} = \frac{j_N RE_N A_F b}{D_N^2 V_{os}}$	$\frac{NTU_s}{V_{os}} = \frac{j_s RE\ A_F b}{D_N^2 V_{os}}$	$\frac{P_e}{V_{os}} = \frac{f_N RE_N^3\ A_F b}{D_N^4 V_{os}}$	$\frac{P_s}{V_{os}} = \frac{f_s RE^3 A_F b}{D_N^4 V_{os}}$
10000	599.03	79.14	8.19 EE 10	2.98 EE 10
.20000	883.32	120.29	5.67 EE 11	2.24 EE 11
30000	1103.45	153.67	1.76 EE 12	7.30 EE 11
40000	1282.99	182.83	3.93 EE 12	1.69 EE 12
50000	1449.00	209.21	7.33 EE 12	3.23 EE 12
60000	1592.89	233.57	1.22 EE 13	5.49 EE 12
70000	1723.54	256.36	1.88 EE 13	8.59 EE 12
80000	1843.57	277.89	2.74 EE 13	1.27 EE 13
90000	1954.80	298.38	3.78 EE 13	1.79 EE 13
100000	2058.60	317.99	5.08 EE 13	2.43 EE 13
110000	2155.99	336.83	6.63 EE 13	3.20 EE 13
120000	2247.82	355.00	8.45 EE 13	4.12 EE 13
130000	2334.72	372.59	1.06 EE 14	5.21 EE 13
	$[1/in^2]$	$[1/in^2]$	$[1/in^4]$	$[1/in^4]$

---

[1] Assumes Aluminum Fin Material & Air @ 90°F

FINNED CIRCULAR TUBES
SURFACE 7.75 - 5/8 T
(Data of Trane Co.)

Tube outside diameter - 0.676 in.
Fin pitch - 7.75 per inch
Flow passage hydraulic diameter - $4r_h$ = 0.01268 ft.
Fin thickness - 0.016 in.
Free-flow area/frontal area - σ = 0.497
Heat transfer area/total volume - α = 157 $ft.^2/ft.^3$
Fin area total area - 0.905

Note: Minimum free-flow area in spaces transverse to flow.
These data are included in this compilation because they apply to a compact surface configuration of considerable technical interest for which no data have been obtained on this project.

D_N = 2.7160

$\frac{RE_N}{RE}$ = 16.1715

$\frac{f_N}{f}$ = 21.7461

$\frac{A_F b}{V_{os}}$ = 1.2727

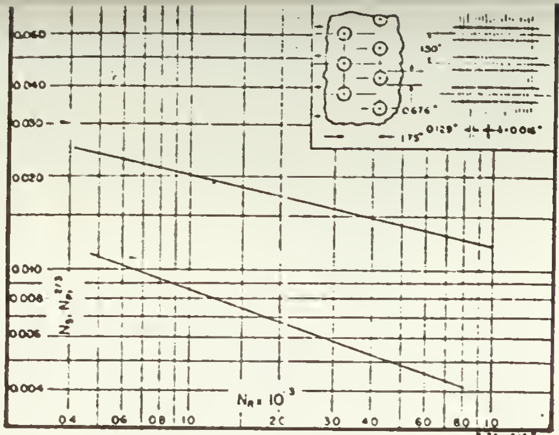


FIG 101

NOT

AVAILABLE

Heat Transfer and

Friction Data

APPENDIX I PROGRAM CONSTANTS						REYNOLDS NUMBER $[RE]_N$	$\frac{NTU_e}{V_{os}} = \frac{j_N RE_N A_F b}{D_N^2 V_{os}}$	$\frac{NTU_s}{V_{os}} = \frac{j_s RE\ A_F b}{D_N^2 V_{os}}$	$\frac{P_e}{V_{os}} = \frac{f_N RE_N^3 A_F b}{D_N^4 V_{os}}$	$\frac{P_s}{V_{os}} = \frac{f_s RE^3 A_F b}{D_N^4 V_{os}}$
0	RE	0.00	10	A_f/A_T	0.905	10000	277.87	24.79	1.14 EE 10	3.44 EE 09
1	$A_{f(e)}$	0.0966	11	ℓ	0.6616	20000	410.58	37.68	7.81 EE 10	2.66 EE 10
2	$B_{f(e)}$	-0.2270	12	ϕ[1]	1.2 EE -4	30000	508.56	48.14	2.40 EE 11	8.77 EE 10
3	$A_{f(s)}$	0.2408	13	$A_{j(e)}$	0.0940	40000	587.05	57.27	5.34 EE 11	2.05 EE 11
4	$B_{f(s)}$	-0.0534	14	$B_{j(e)}$	-0.3458	50000	652.48	65.54	9.92 EE 11	3.95 EE 11
5	D_{2h}	0.1522	15	δ	0.0160	60000	708.37	73.16	1.64 EE 12	6.76 EE 11
6	Δ_1	-0.00259	16	$A_{j(s)}$	0.5514	70000	756.38	80.30	2.52 EE 12	1.06 EE 12
7	Δ_2	-0.00835	17	$B_{j(s)}$	-.3960	80000	799.47	87.05	3.65 EE 12	1.58 EE 12
8	Δ_3	-0.02426	18	Fin ID	-1.000	90000	837.17	93.47	5.06 EE 12	2.23 EE 12
9	Δ_4	-0.45203	19	ρ	0.3381	100000	870.76	99.61	6.73 EE 12	3.05 EE 12
A	Data ID	101.00	D	X_L	2.5888	110000	900.84	105.51	8.33 EE 12	4.03 EE 12
B	β	13.083	E	X_T	2.2189	120000	927.87	111.20	1.12 EE 13	5.21 EE 12
C	D_o	0.676	I	Incr'mt	10000	130000	952.22	116.71	1.40 EE 13	6.60 EE 12
							$[1/in^2]$	$[1/in^2]$	$[1/in^4]$	$[1/in^4]$

[1] Assumes Aluminum Fin Material & Air @ 90°F

FINNED CIRCULAR TUBES
(data of Trane Co.)

Tube outside Dia: 0.391 in
Fin Pitch: 8.0 per in
Flow Pass. Hyd. Dia.: .01268 ft.
Fin Thickness: 0.008 in
Total Transfer area/Tot. Vol: 180 ft^2/ft^3
Fin area/Tot. Area: .916

D_N = 1.7174

$\frac{f_N}{f}$ = 12.8670

$\frac{RE_N}{RE}$ = 10.5751

$\frac{A_F b}{V_{os}}$ = 1.4141

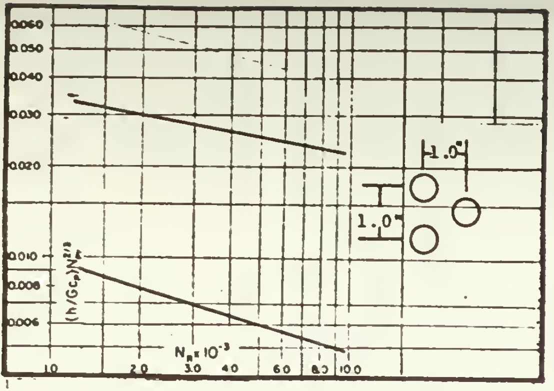


FIG 102 SPECIAL

NOT

AVAILABLE

Heat Transfer and

Friction Data

APPENDIX I PROGRAM CONSTANTS

0	RE	0.0000	10	A_f/A_T	0.9160
1	$A_{f(e)}$	0.1367	11	ℓ	0.3295
2	$B_{f(e)}$	-0.1938	12	k[1]	6.23 EE -05
3	$A_{f(s)}$	0.3501	13	$A_{j(e)}$	0.0814
4	$B_{f(s)}$	-0.0841	14	$B_{j(e)}$	-0.3073
5	D_{2h}	0.1522	15	δ	0.0080
6	Δ_1	-0.00259	16	$A_{j(s)}$	0.6003
7	Δ_2	-0.00835	17	$B_{j(s)}$	-0.3960
8	Δ_3	-0.02426	18	Fin ID	-1.0000
9	Δ_4	-0.45208	19	ρ	0.3724
A	Data ID	102 SPECIAL	D	X_L	2.2148
B	β	15.0000	E	X_T	2.5575
C	D_o	0.3910	I	Incr'mt	10000

REYNOLDS NUMBER $[RE]_N$	$\frac{NTU_e}{V_{os}} = \frac{j_N RE_N A_F b}{D_N^2 V_{os}}$	$\frac{NTU_s}{V_{os}} = \frac{j_s RE\ A_F b}{D_N^2 V_{os}}$	$\frac{P_e}{V_{os}} = \frac{f_N RE_N^3\ A_F b}{D_N^4 V_{os}}$	$\frac{P_s}{V_{os}} = \frac{f_s RE^3 A_F b}{D_N^4 V_{os}}$
10000	510.07	75.00	7.57 EE 10	2.62 EE 10
20000	802.42	114.00	5.30 EE 11	1.98 EE 11
30000	1038.78	145.63	1.65 EE 12	6.46 EE 11
40000	1242.49	173.27	3.70 EE 12	1.49 EE 12
50000	1423.59	198.27	6.93 EE 12	2.8 EE 12
60000	1587.63	221.35	1.16 EE 13	4.87 EE 12
70000	1738.10	242.95	1.78 EE 13	7.64 EE 12
80000	1877.38	263.35	2.59 EE 13	1.13 EE 13
90000	2007.21	282.77	3.61 EE 13	1.59 EE 13
100000	2128.89	301.35	4.85 EE 13	2.16 EE 13
110000	2243.43	319.21	6.33 EE 13	2.85 EE 13
120000	2351.66	336.43	8.08 EE 13	3.68 EE 13
130000	2454.24	353.10	1.01 EE 14	4.64 EE 14
	$[1/in^2]$	$[1/in^2]$	$[1/in^4]$	$[1/in^4]$

[1] Assumes Copper Fin Material & Air @ 90°F

APPENDIX III

SIZING CROSSFLOW FINNED TUBULAR HEAT EXCHANGERS FOR A GIVEN JOB

Crossflow finned tubular heat exchangers have found application as gas turbine plant intercoolers, air conditioning unit heat exchangers, aircraft engine coolers, and numerous other uses. These applications most often involve gas-liquid service.

The "job" of the heat exchanger will be defined as transfering a specified amount of heat between two fluids at given flow rates (W) and with specified amounts of pumping power on each side. The following values are specified:

W_1, T_{in_1}, T_{out_1}, ΔP_1, P_{in_1}, D_{1h}, Properties_1

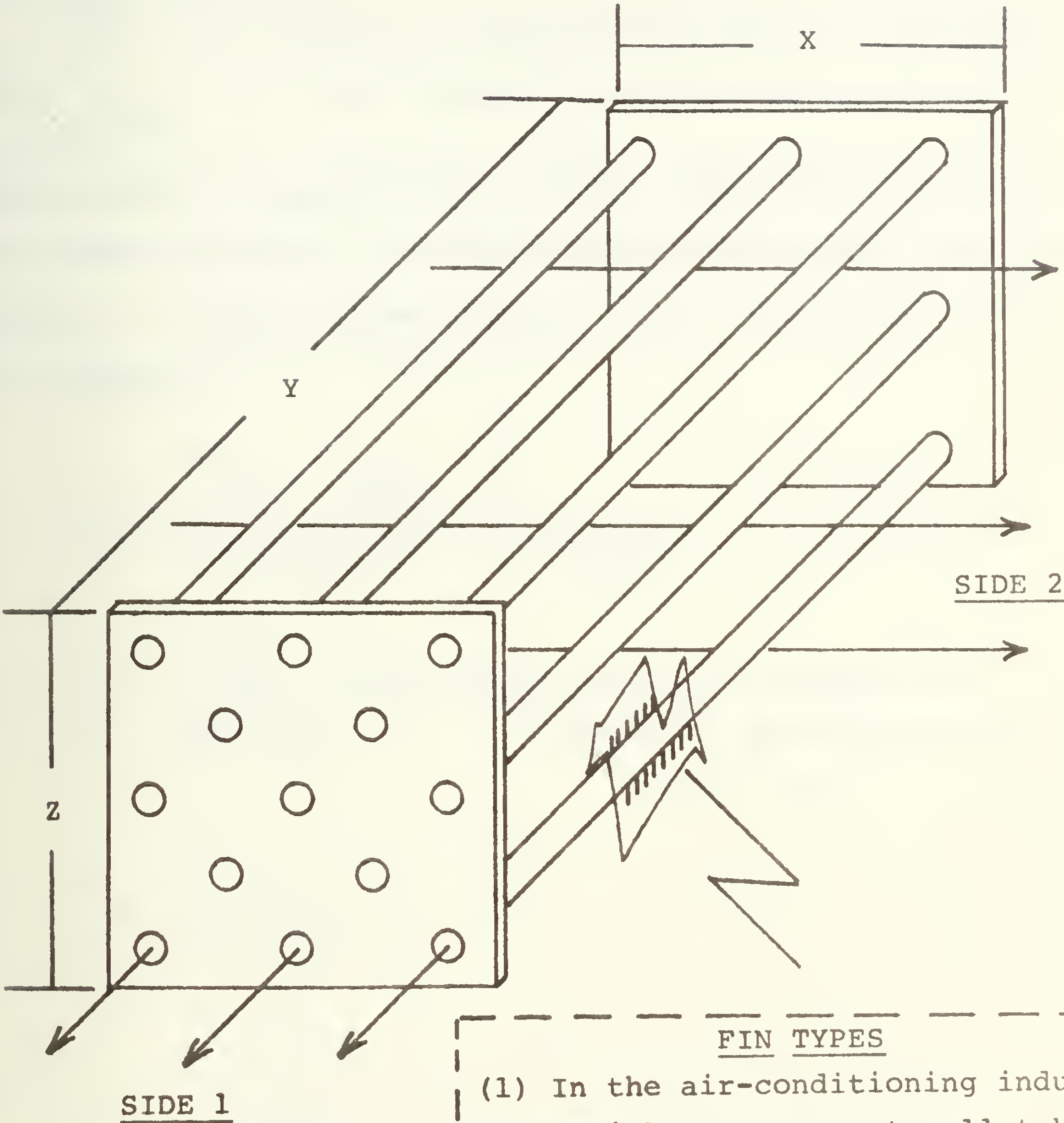
W_2, T_{in_2}, T_{out_2}, ΔP_2, P_{in_2}, D_{2h}, Properties_2

Subscript 1 will refer to the hotter fluid inside the smooth tubes and subscript 2 to the colder fluid flowing over finned tube banks.

While core pressure drop accounts for by far the greatest percentage of the total pressure drop, entrance and exit losses would have to be included in the final design. [Ref 1 Chapter 4]

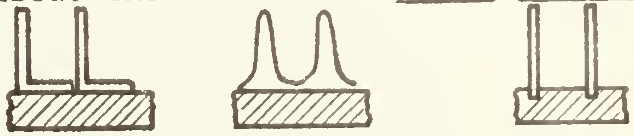
Figure A-1 shows the heat exchanger arrangement.

FIGURE A-1



FIN TYPES

(1) In the air-conditioning industry, fins which are common to all tubes in the bundle as distinct from having each tube separately finned are often used. This is called plate finning.



(2) L-fins (3) Extruded (4) G-fins

The Basic Equations

The first portion of the procedure involves determination of A_{c_1}, A_{c_2}, X, Y, and Z based on the specified values of ΔP_1 and ΔP_2 and an assumed value of RE_2. Then based on heat transfer considerations, it is determined if the proper heat balance exists. If not, another value of RE_2 is assumed and the process is repeated.

$$\beta_1 = \frac{4\ A_{c_1}}{D_{1h}\ A_{fr_1}} = \left[\frac{\pi\ D_{1h}}{F\ b}\right]_{\text{for round tubes}} \qquad D_{1h} = D_{inside} \tag{1}$$

$$\beta_2 = \frac{4\ A_{c_2}}{D_{2h}\ A_{fr_2}} = \text{A specified geometric constant for surface 2; See Figure A-II } [D_{2h} = 4r_h] \tag{2}$$

$$\frac{A_{c_1}}{A_{fr_1}} = \beta_1 \frac{D_{1h}}{4} = K_1 \tag{3}$$

$$\frac{A_{c_2}}{A_{fr_2}} = \beta_2 \frac{D_{2h}}{4} = K_2 \tag{4}$$

$$A_{c_1} = [\beta_1 \frac{D_{1h}}{4}]\ [XZ] = K_1\ X\ Z \tag{5}$$

$$A_{c_2} = [\beta_2 \frac{D_{2h}}{4}] \; [YZ] = K_2 \; Y \; Z \qquad (6)$$

$$G = \frac{W}{A_c} \qquad (7)$$

$$\frac{G_1}{G_2} = \frac{[W_1/A_{c_1}]}{[W_2/A_{c_2}]} = \frac{[W_1] \; [A_{c_2}]}{[W_2] \; [A_{c_1}]} \qquad (8)$$

From equations (5) and (6):

$$\frac{G_1}{G_2} = \frac{[W_1] \; [K_2 \; YZ]}{[W_2] \; [K_1 \; XZ]} = K_3 \; \frac{Y}{Z} \qquad (9)$$

where $K_3 = \frac{W_1 \; K_2}{W_2 \; K_1}$

$$\Delta P = \frac{4 \; f \; L \; G^2}{D_{1h} \; 2 \; g_o \; \rho_m} \qquad (10)$$

where L is the flow length:

Side 1: L = Y

Side 2: L = X

$$\frac{G_1^2}{G_2^2} = \frac{[\Delta P_1 \; D_{1h} \; \rho_{m1}] \; [f_2] \; [X]}{[\Delta P_2 \; D_{2h} \; \rho_{m2}] \; [f_1] \; [Y]} \tag{11}$$

Define $K_4 = \dfrac{[\Delta P_1 \; D_{1h} \; \rho_{m1}]}{[\Delta P_2 \; D_{2h} \; \rho_{m2}]}$

From Equations (9) and (11):

$$\frac{G_1^2}{G_2^2} = K_4 \; \frac{[f_2] \; [X]}{[f_1] \; [Y]} = K_3^2 \; \frac{[Y]^2}{[X]^2} \tag{12}$$

or

$$\frac{f_2}{f_1} = \frac{K_3^2 \; [Y]^3}{K_4 \; [X]^3} = K_5 \; \frac{[Y]^3}{[X]^3} \tag{13}$$

where $K_5 = \dfrac{K_3^2}{K_4}$

Eliminate [Y/X] with equations (9) and (13):

$$\frac{f_2}{f_1} = \frac{[G_1]^3}{[G_2]^3} \; \frac{[K_5]}{[K_3]^3} = K_6 \frac{[G_1]^3}{[G_2]^3} \tag{14}$$

$$\text{where } K_6 = \frac{K_5}{K_3^3} = \frac{\Delta P_2 \; \rho_2 \; \beta_1 \; W_2}{\Delta P_1 \; \rho_1 \; \beta_2 \; W_1}$$

$$G = \frac{RE \; \mu}{D_h}$$

Substitution in equation (14) yields:

$$\frac{f_2}{f_1} = K_6 \frac{[RE_1^3 \; \mu_1^3 \; D_{2h}^3]}{[RE_2^3 \; \mu_2^3 \; D_{1h}^3]} \tag{15}$$

$$RE_1^3 \; f_1 = \frac{f_2 \; RE_2^3 \; \mu_2^3 \; D_{1h}^3}{K_6 \qquad \mu_1^3 \; D_{2h}^3} \tag{16}$$

Solving for RE_1:

$$RE_1 = \left[\frac{f_2 \; RE_2^3 \; \mu_2^3 \; D_{1h}^3}{f_1 \; K_6 \quad \mu_1^3 \; D_{2h}^3}\right]^{0.333} \tag{16a}$$

To begin the design procedure, a value of RE_2 is assumed. Use the f_2 verses RE plot for side 2 to determine f_2. A sample data plot from reference [2] along with the associated geometric parameters describing a typical side 2 flow arrangement is shown in Figure A-II.

FIGURE A-II

SAMPLE DATA PLOT FOR SURFACE 2

[REF 2]

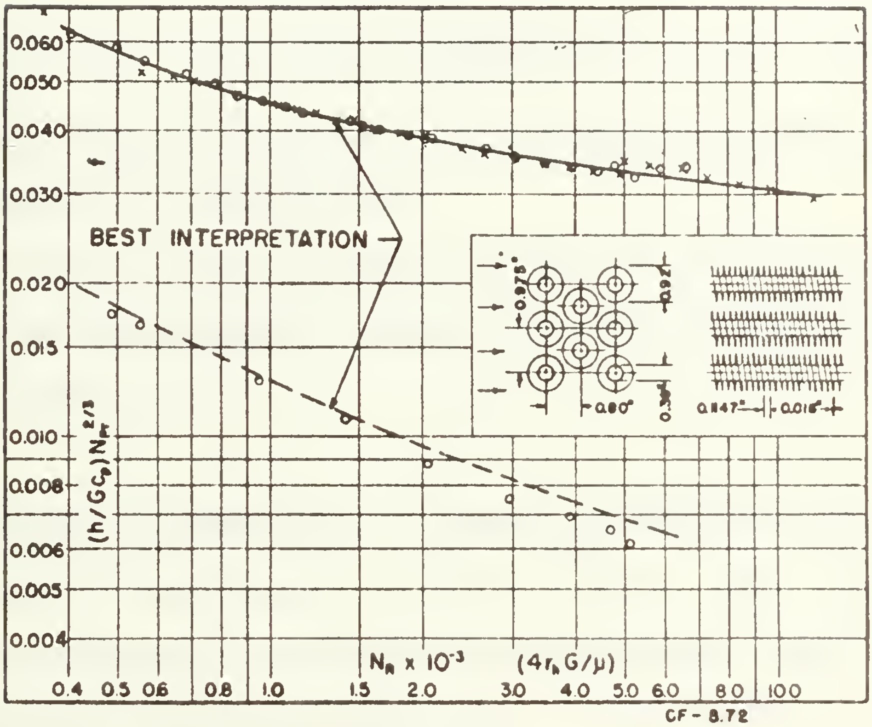


FIG. 93

FINNED CIRCULAR TUBES
SURFACE CF - 8.72

Tube outside diameter - 0.38 in.
Fin pitch - 8.72 per inch
Flow passage hydraulic diameter - $4r_h$=0.01288 ft.
Fin thickness (average)* - 0.018 in.
Free-flow area/frontal area -.σ=0.524
Heat transfer area/total volume - α=163 $ft.^2/ft.^3$
Fin area/total area - 0.910

Note: Experimental uncertainty for heat transfer results possibly somewhat greater than the nominal ±5% quoted for the other surfaces because of the necessity of estimating a contact resistance in the bi-metal tubes.

* - Fins slightly tapered.

It should be noted that the friction factor verses RE plot for flow over finned tube banks can be closely approximated by a straight line on a Log-Log plot. This implies that f_2 can be accurately represented by an equation of the form:

$$f_2 = A_f[RE]^{B_f}$$

Table I list the linearized equations of f_2 [and j_2] for Figures 92-101 of reference [2].

This simplification allows for ease in programming as demonstrated in the suggested design procedure flow diagram outlined in Table II.

For exact calculations, f_1 should be read from the f_1 verses RE plot for the specific tubular surface under investigation, if such data is available. From this plot for surface 1, it is possible to determine RE_1 and f_1 to satisfy equation (16) or (16a) once a value of RE_2 has been assumed.

If, after assuming a value of RE_2, the required value of f_1 and RE_1 lay outside the range of data for surface 1, a new value of RE_2 must be assumed.

If the required data for surface 1 is not available, friction factor for turbulent flow inside smooth tubes is well correlated and given by Nikuradse as:

$$\frac{1}{\sqrt{f}} = 4.0 \operatorname{Log}_{10}[RE \sqrt{f}] - 0.40 \qquad (17)$$

The transition from laminar to turbulent flow inside smooth tubes occurs between Reynolds number of 2300 and 4000.

Excellent linear approximations of the Nikuradse relation are given by:

$$f_1 \simeq 0.0791\ RE^{-0.25} \qquad 2300 < RE < 20{,}000 \qquad (18)$$

$$f_1 \simeq 0.0460\ RE^{-0.20} \qquad 20{,}000 < RE < 10^7 \qquad (19)$$

In a crossflow finned tubular heat exchanger the dominant heat transfer resistance will probably be the gas outside the tubes flowing over the fins (side 2). It is for this reason that high accuracy for the f (and j) prediction of the fluid on side 1 is not critical.

Note that equation (16a), using the linear approximation for f_1 given by equation (18) may be rewritten as:

$$RE_1 = \left[\frac{f_2\ RE_2^3\ \mu_2^3\ D_{1h}^3}{0.0791\ K_6\ \mu_1^3\ D_{2h}^3}\right]^{.3636} \qquad (20)$$

Having satisfied either equation (16) using f_1 verses RE_1 data for the specific tubular surface under investigation, OR equation (20) using the specified linear approximation for turbulent flow inside smooth tubes, length dimensions X and Y may be calculated from the relations given in equation (10):

$$X = \frac{\Delta P_2 \; D_{2h}^3 \; g_o \; \rho_2}{2 \; f_2 \; RE_2^2 \; \mu_2^2} \tag{22}$$

$$Y = \frac{\Delta P_1 \; D_{1h}^3 \; g_o \; \rho_1}{2 \; f_1 \; RE_1^2 \; \mu_1^2} \tag{23}$$

Length Z may be calculated from equations (5) and (7):

$$Z = \frac{4 \; W_1}{\beta_1 \; RE_1 \; \mu_1 \; X} \tag{24}$$

The number of tubes can be determined from:

$$N = \frac{X \; Z}{F \; b} = \frac{W_1 \; D_{1h}}{RE_1 \; \mu_1 \; A_{c_1}} \tag{25}$$

As was the case for friction factor, j_1 should be read from the j_1 verses RE plot for the specific tubular surface under investigation, if available.

In the event that the actual heat transfer data for side 1 is not available, correlations can be used without introducing significant deviations as explained earlier.

The Colburn correlation for forced-convection, turbulent flow in tubes is widely accepted:

$$j_1 = 0.023 \; RE^{-0.20} \tag{27}$$

The heat transfer coefficient [h] may be defined as:

$$h_1 = \frac{j_1 \; C_{p1} \; \mu_1 \; RE_1}{Pr_1^{.667} \; D_{1h}} \tag{28}$$

Or using the Colburn correlation expressed by equation (27):

$$h_1 = \frac{0.023 \; RE^{0.80} \; C_{p1} \; \mu_1}{Pr_1^{.667} \; D_{1h}} \tag{28a}$$

The value of j_2 should be read from the j_2 verses RE plot for surface 2. As was the case for f_2, the Colburn modulus can be expressed in an equation of the form:

$$j_2 = A_j \; RE^{B_j}$$

Table I presents the linearized equations of j_2 for Figures 92-101 of reference [2].

$$h_2 = \frac{j_2 \ C_{p2} \ \mu_2 \ RE_2}{P_r^{.667} \ D_{2h}} \tag{29}$$

Refering to Figure A-III, calculate the appropriate value of fin and surface efficiency for side 2:

$$\frac{1}{AU} = \frac{1}{A_{T_1} \ U_1} = \frac{1}{A_{T_2} \ U_2} = \frac{1}{A_{T_1} \ h_1} + \frac{1}{A_{T_2} \ \eta_{o_2} \ h_2} \tag{33}$$

where:

$$A_{T_1} = \alpha_1 \ XYZ$$

$$A_{T_2} = \alpha_2 \ XYZ$$

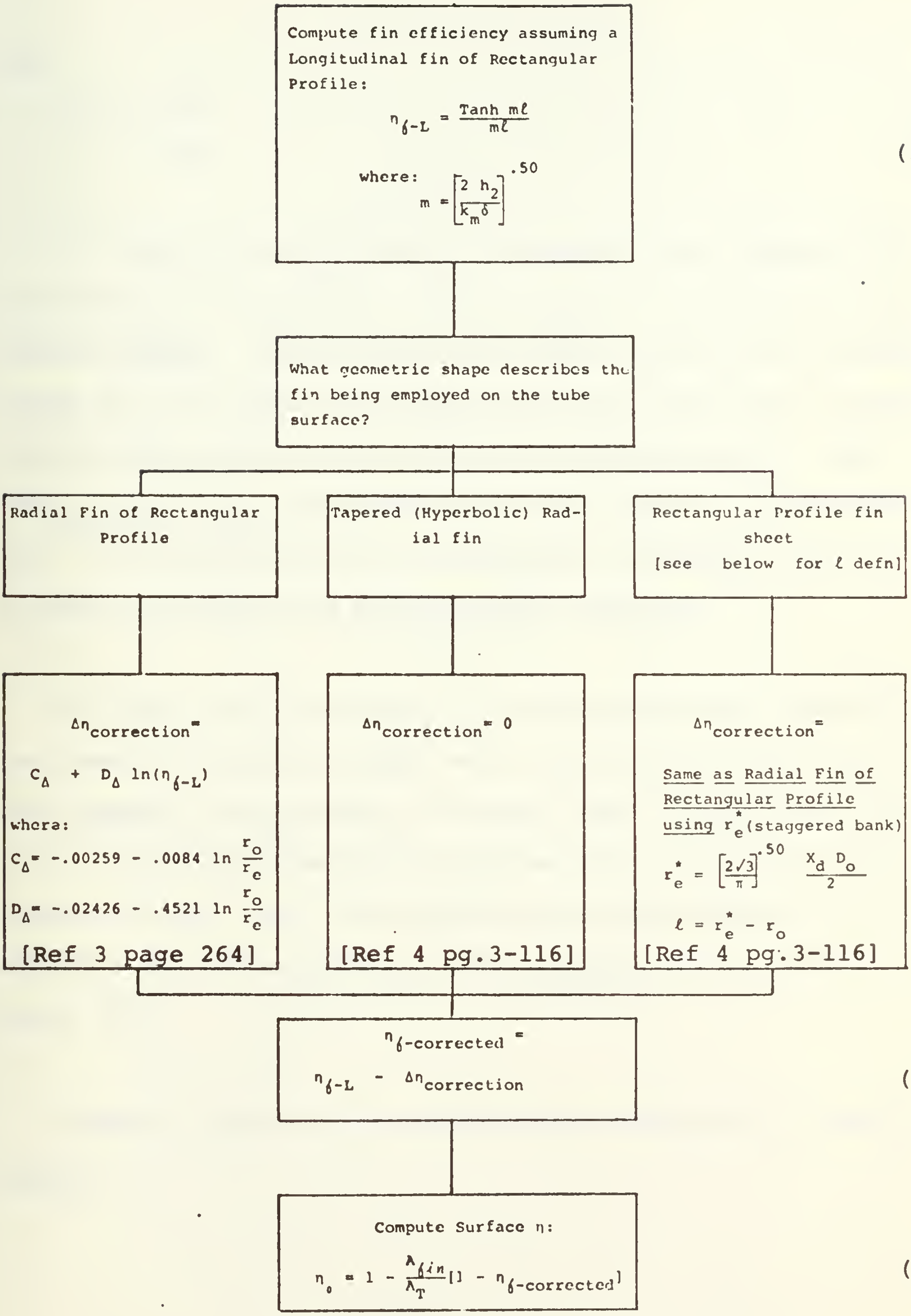
If $C_1 < C_2$, $C_{min} = C_1$, $C_{min}/C_{max} = C_1/C_2$

$$\varepsilon = \frac{T_{in_1} - T_{out_1}}{T_{in_1} - T_{in_2}} \tag{34a}$$

If $C_2 < C_1$, $C_{min} = C_2$, $C_{min}/C_{max} = C_2/C_1$

$$\varepsilon = \frac{T_{out_2} - T_{in_2}}{T_{in_1} - T_{in_2}} \tag{34b}$$

FIGURE A-III



Compute fin efficiency assuming a Longitudinal fin of Rectangular Profile:

$$\eta_{f-L} = \frac{\text{Tanh } m\ell}{m\ell} \qquad (30)$$

where:

$$m = \left[\frac{2\ h_2}{k_m \delta}\right]^{.50}$$

What geometric shape describes the fin being employed on the tube surface?

Radial Fin of Rectangular Profile

$\Delta\eta_{correction} =$

$C_\Delta + D_\Delta \ln(\eta_{f-L})$

where:

$C_\Delta = -.00259 - .0084 \ln \frac{r_o}{r_e}$

$D_\Delta = -.02426 - .4521 \ln \frac{r_o}{r_e}$

[Ref 3 page 264]

Tapered (Hyperbolic) Radial fin

$\Delta\eta_{correction} = 0$

[Ref 4 pg.3-116]

Rectangular Profile fin sheet [see below for ℓ defn]

$\Delta\eta_{correction} =$

Same as Radial Fin of Rectangular Profile using r_e^* (staggered bank)

$r_e^* = \left[\frac{2\sqrt{3}}{\pi}\right]^{.50} \frac{X_d\ D_o}{2}$

$\ell = r_e^* - r_o$

[Ref 4 pg.3-116]

$$\eta_{f\text{-corrected}} = \eta_{f-L} - \Delta\eta_{correction} \qquad (31)$$

Compute Surface η:

$$\eta_o = 1 - \frac{A_{fin}}{A_T}[1 - \eta_{f\text{-corrected}}] \qquad (32)$$

also

$$NTU = \frac{A\ U}{C_{min}} \tag{35}$$

If side 2 is in the form of rectangular fin sheets, the gas flowing over the tubes and the fluid in the tubes are considered UNMIXED. Using Figure A-IV with C_{min}/C_{max} and the magnitude of ε calculated from equation (34a or 34b) read the magnitude of NTU required to produce this effectiveness. Find $[NTU_{required}][C_{min}]$ and compare with the results of equation (33). If the equation is not balanced, a different value of RE_2 must be assumed and the procedure repeated.

If side 2 is in the form of low fins, the gas flowing over the tubes is considered MIXED while the fluid in the tubes remains UNMIXED. The procedure outlined above is used with Figure A-V to find the NTU required to produce the calculated effectiveness in this case. An alternative to using Figure A-V is to calculate the NTU requirement from equation (14) or (15) of reference [2].

Table II presents the entire design procedure in a flow diagram.

FIGURE A-IV

[BOTH FLUIDS UNMIXED]

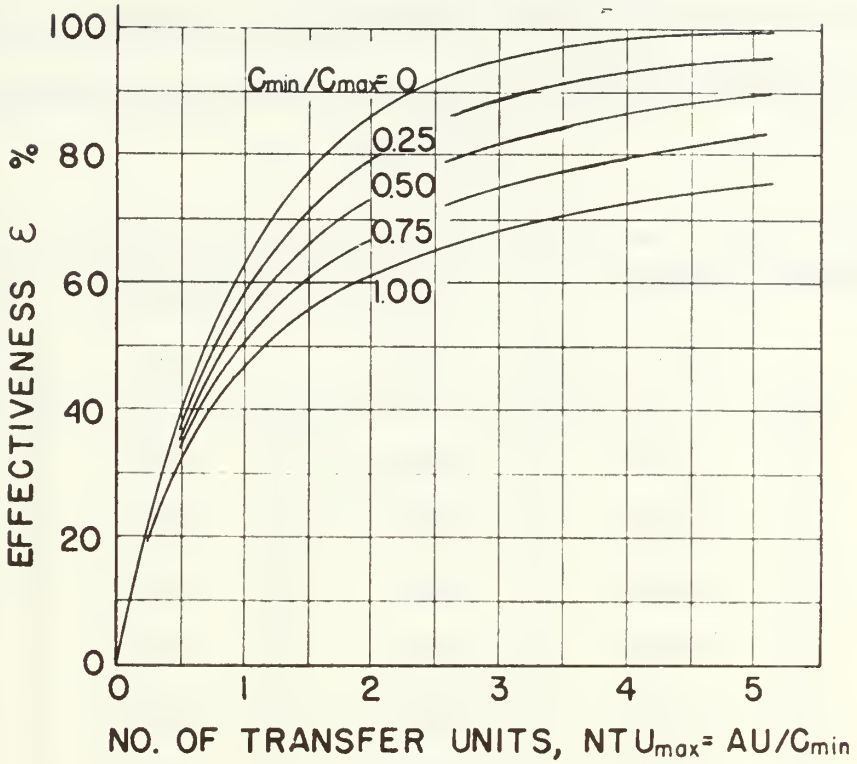


FIGURE A-V

[ONE FLUID MIXED; ONE FLUID UNMIXED]

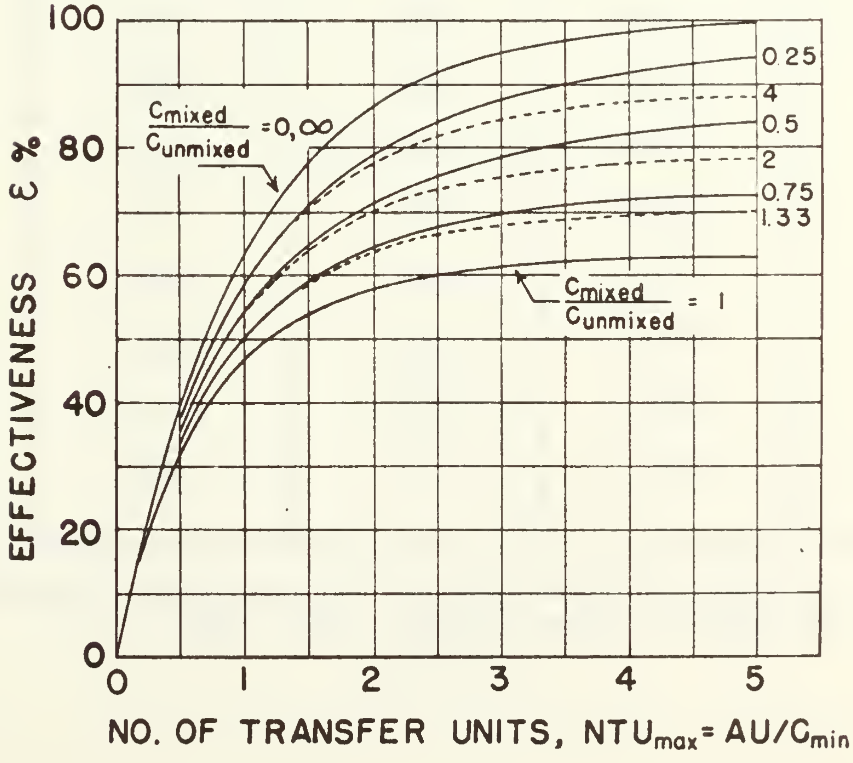


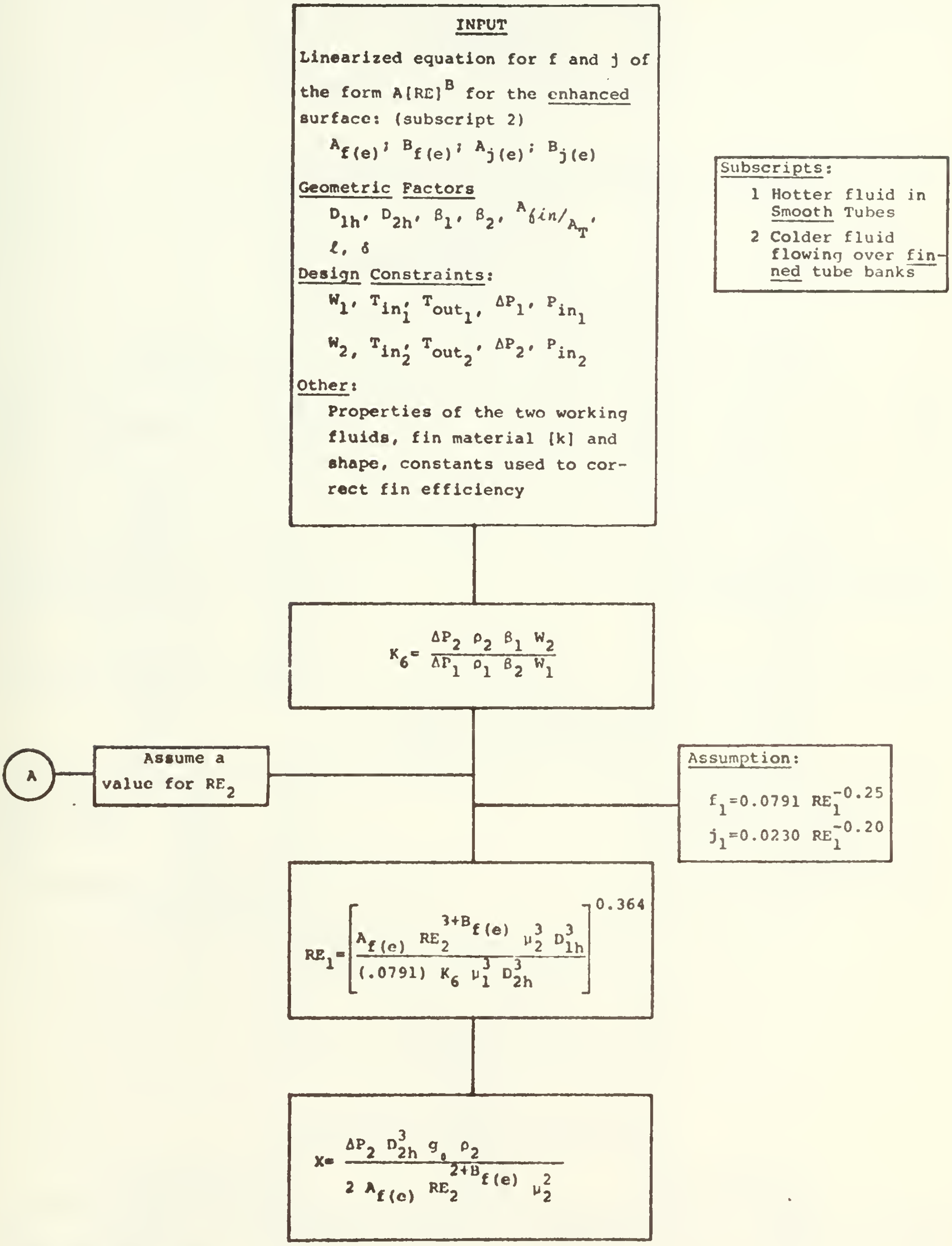
TABLE I

LINEARIZED EQUATIONS OF THE FORM A $[RE]^B$ FOR FRICTION FACTOR & COLBURN MODULUS FOR FINNED TUBULAR SURFACES PRESENTED IN REFERENCE [2]

FIGURE	FRICTION FACTOR [f]		COLBURN MODULUS [j]	
	A_f	B_f	A_j	B_j
92	.1781	-.1954	.3311	-.4804
93	.1862	-.2016	.2262	-.4127
94	.2377	-.2192	.2254	-.4027
96	.2646	-.2559	.1461	-.3418
97A	.2319	-.2454	.1541	-.3596
97B	.5416	-.2676	.2163	-.3666
98A	.2263	-.2707	.0842	-.3273
98B	.2905	-.2531	.0947	-.3239
98C	.3850	-.2462	.1023	-.3137
98D	.2173	-.2590	.0813	-.3264
98E	.3020	-.2607	.0915	-.3288
99A	.1542	-.2478	.1432	-.3726
99B	.3599	-.2563	.2027	-.3787
100	.1223	-.2173	.1650	-.3986
101	.0966	-.2270	.0940	-.3458

NOTE: These equations are written for the range:
$1000 < RE <$ upper limit of data IAW Ref [2]

CROSSFLOW FINNED TUBULAR HEAT EXCHANGER DESIGN PROCEDURE



INPUT

Linearized equation for f and j of the form $A[RE]^B$ for the enhanced surface: (subscript 2)

$A_{f(e)}$; $B_{f(e)}$; $A_{j(e)}$; $B_{j(e)}$

Geometric Factors

D_{1h}, D_{2h}, β_1, β_2, A_{fin}/A_T, ℓ, δ

Design Constraints:

W_1, T_{in_1}, T_{out_1}, ΔP_1, P_{in_1}

W_2, T_{in_2}, T_{out_2}, ΔP_2, P_{in_2}

Other:

Properties of the two working fluids, fin material [k] and shape, constants used to correct fin efficiency

Subscripts:

1 Hotter fluid in Smooth Tubes

2 Colder fluid flowing over finned tube banks

$$K_6 = \frac{\Delta P_2 \; \rho_2 \; \beta_1 \; W_2}{\Delta P_1 \; \rho_1 \; \beta_2 \; W_1}$$

Assume a value for RE_2

Assumption:

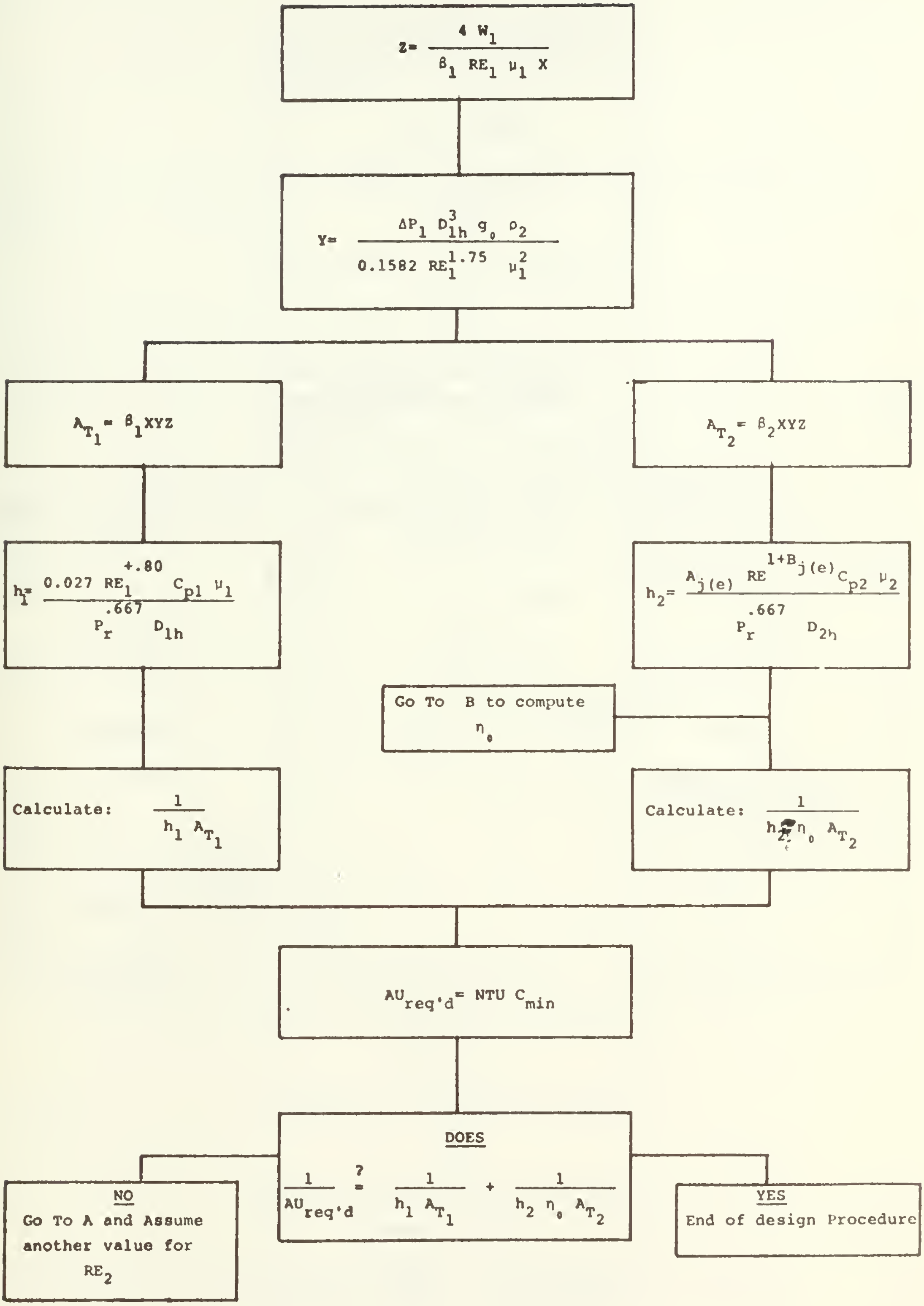
$f_1 = 0.0791 \; RE_1^{-0.25}$

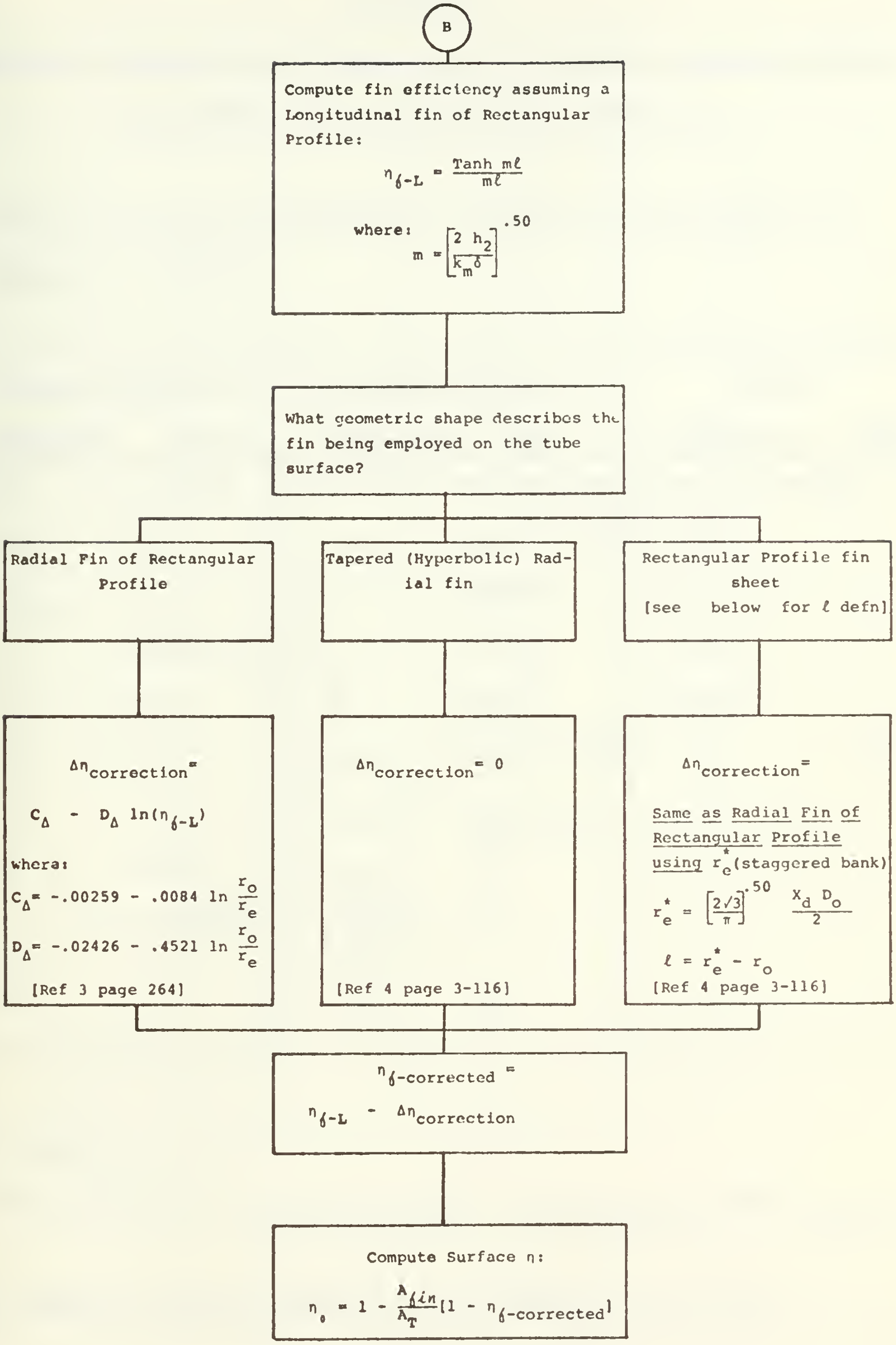
$j_1 = 0.0230 \; RE_1^{-0.20}$

$$RE_1 = \left[\frac{A_{f(e)} \; RE_2^{3+B_{f(e)}} \; \mu_2^3 \; D_{1h}^3}{(.0791) \; K_6 \; \mu_1^3 \; D_{2h}^3} \right]^{0.364}$$

$$X = \frac{\Delta P_2 \; D_{2h}^3 \; g_c \; \rho_2}{2 \; A_{f(e)} \; RE_2^{2+B_{f(e)}} \; \mu_2^2}$$

TABLE II


$Z = \frac{4 W_1}{\beta_1 RE_1 \mu_1 X}$
$Y = \frac{\Delta P_1 D_{1h}^3 g_0 \rho_2}{0.1582 RE_1^{1.75} \mu_1^2}$
$A_{T_1} = \beta_1 XYZ$
$A_{T_2} = \beta_2 XYZ$
$h_1 = \frac{0.027 RE_1^{+.80} C_{p1} \mu_1}{P_r^{.667} D_{1h}}$
$h_2 = \frac{A_{j(e)} RE^{1+B_{j(e)}} C_{p2} \mu_2}{P_r^{.667} D_{2h}}$
Go To B to compute η_0
Calculate: $\frac{1}{h_1 A_{T_1}}$
Calculate: $\frac{1}{h_2 \eta_0 A_{T_2}}$
$AU_{req'd} = NTU\ C_{min}$
DOES
$\frac{1}{AU_{req'd}} \overset{?}{=} \frac{1}{h_1 A_{T_1}} + \frac{1}{h_2 \eta_0 A_{T_2}}$
NO
Go To A and Assume another value for RE_2
YES
End of design Procedure



Compute fin efficiency assuming a Longitudinal fin of Rectangular Profile:

$$\eta_{f\text{-}L} = \frac{\tanh m\ell}{m\ell}$$

where:

$$m = \left[\frac{2\ h_2}{k_m \delta}\right]^{.50}$$

What geometric shape describes the fin being employed on the tube surface?

Radial Fin of Rectangular Profile

Tapered (Hyperbolic) Radial fin

Rectangular Profile fin sheet [see below for ℓ defn]

$\Delta\eta_{correction} =$

$C_\Delta - D_\Delta \ln(\eta_{f\text{-}L})$

where:

$$C_\Delta = -.00259 - .0084 \ln \frac{r_o}{r_e}$$

$$D_\Delta = -.02426 - .4521 \ln \frac{r_o}{r_e}$$

[Ref 3 page 264]

$\Delta\eta_{correction} = 0$

[Ref 4 page 3-116]

$\Delta\eta_{correction} =$

Same as Radial Fin of Rectangular Profile using r_e^* (staggered bank)

$$r_e^* = \left[\frac{2\sqrt{3}}{\pi}\right]^{.50} \frac{X_d\ D_o}{2}$$

$$\ell = r_e^* - r_o$$

[Ref 4 page 3-116]

$$\eta_{f\text{-}corrected} = \eta_{f\text{-}L} - \Delta\eta_{correction}$$

Compute Surface η:

$$\eta_o = 1 - \frac{A_{fin}}{A_T}[1 - \eta_{f\text{-}corrected}]$$

TABLE III

SUGGESTED PROGRAM FOR SIZING CROSSFLOW FINNED TUBULAR HEAT EXCHANGERS FOR A GIVEN JOB IAW TABLE II*

I. Design Constraints/Geometric Constants to be stored in Memory as follows:

	Primary Register			Secondary Register			Other	
	Quantity	Units		Quantity	Units		Quantity	Units
0	ΔP_2	LB/FT^2	0	$C_{P2}/P_r^{.667}$	BTU/LBM-F	A	RE_2 (assumed)	ND
1	$A_{f(e)}$	ND	1	$g_o \rho_{m2}$	$LBM/HR^2\text{-}FT^2$	B	0.00	
2	$B_{f(e)}$	ND	2	W_1	LBM/HR	C	0.00	
3	μ_2	LB/HR-FT	3	β_1	FT^2/FT^3	D	0.00	
4	D_{1h}	FT	4	ΔP_1	LB/FT^2	E	A_δ/A_T	ND
5	C_Δ	ND	5	$g_o \rho_{m1}$	$LBM/HR^2\text{-}FT^2$	I	β_2	FT^2/FT^3
6	D_Δ	ND	6	$C_{p1}/P_r^{.667}$	BTU/LBM-F			
7	W_1	LB/HR	7	$A_{j(e)}$	ND			
8	μ	LB/HR-FT	8	$\dfrac{C_{p2}\mu_2 \ell^2}{K_m P_r^{.667}\delta}$	FT			
9	D_{2h}	FT	9	$B_{j(e)}$	ND			

II. OUTPUT

RE_1, X, Z, Y, $\Delta\eta_{\text{to be applied}}$, $\eta_{\delta\text{-corrected}}$, $[NTU\ C_{min}]_{\text{cal'td}}$

*For Hewlett-Packard HP-67/97 Programmable Calculator

III. PROGRAM FOR SIZING FINNED TUBULAR HEAT EXCHANGERS FOR A GIVEN JOB*

[Table III continued]

```
001  *LBLA    21 11
002   P⇄S     16-51
003   RCL1    36 01
004   RCL3    36 03
005     x       -35
006   RCL4    36 04
007     +       -24
008   RCL5    36 05
009     +       -24
010   RCL2    36 02
011     +       -24
012   RCLI    36 46
013     ÷       -24
014   P⇄S     16-51
015   RCL0    36 00
016     x       -35
017   RCL7    36 07
018     x       -35
019   STO7    35 07
020  *LBLB    21 12
021   RCL3    36 03
022   RCL4    36 04
023     x       -35
024   RCL8    36 08
025     ÷       -24
026   RCL9    36 09
027     +       -24
028     3        03
029    Yˣ        31
030   RCL1    36 01
031     x       -35
032   RCLA    36 11
033   PRTX      -14
034     3        03
035   RCL2    36 02
036     +       -55
037    Yˣ        31
038     x       -35
039     .       -62
040     0        00
041     7        07
042     9        09
043     1        01
044     ÷       -24
045   RCL7    36 07
046     ÷       -24
047     2        02
048     .       -62
049     7        07
050     5        05
051   1/X        52
052    Yˣ        31
053   PRTX      -14
054   STOB    35 12
055   RCL0    36 00
056   RCL3    36 03
057    X²        53
058     ÷       -24
059   RCLA    36 11
060     2        02
061   RCL2    36 02
062     +       -55
063    Yˣ        31
064     ÷       -24
065     2        02
066     +       -24
067   RCL1    36 01
068     ÷       -24
069   RCL9    36 09
070     3        03
071    Yˣ        31
072     x       -35
073   P⇄S     16-51
074   RCL1    36 01
075     x       -35
076   PRTX      -14
077   STOC    35 13
078     4        04
079   RCL2    36 02
080     x       -35
081   RCL3    36 03
082     ÷       -24
083   RCLB    36 12
084     ÷       -24
085   P⇄S     16-51
086   RCL8    36 08
087     ÷       -24
088   RCLC    36 13
099     ÷       -24
090   PRTX      -14
091   RCLC    36 13
092     x       -35
093   STOC    35 13
094   RCL4    36 04
095     3        03
096    Yˣ        31
097   RCLB    36 12
098     1        01
099     .       -62
100     7        07
101     5        05
102    Yˣ        31
103     ÷       -24
104   RCL6    36 06
105    X²        53
106     ÷       -24
107     .       -62
108     1        01
109     5        05
110     6        06
111     2        02
112     ÷       -24
113   P⇄S     16-51
114   RCL4    36 04
115     x       -35
116   RCL5    36 05
117     x       -35
118   PRTX      -14
119   RCLC    36 13
120     x       -35
121   STOC    35 13
122   RCLA    36 11
123   RCL9    36 09
124     1        01
125     +       -55
126    Yˣ        31
127   RCL7    36 07
128     x       -35
129     2        02
130     x       -35
131   RCL8    36 08
132     x       -35
133   P⇄S     16-51
134   RCL9    36 09
135     ÷       -24
136    √X        54
137   STOD    35 14
138    eˣ        33
139   RCLD    36 14
140   CHS       -22
141    eˣ        33
142     -       -45
143   LSTX    16-63
144   RCLD    36 14
145    eˣ        33
146     +       -55
147     ÷       -24
148   RCLD    36 14
149     ÷       -24
150   ENT↑      -21
151    LN        32
152   RCL6    36 06
153   CHS       -22
154     x       -35
155   RCL5    36 05
156     +       -55
157   PRTX      -14
158     -       -45
159   STOD    35 14
160   PRTX      -14
161     1        01
162   RCLD    36 14
163     -       -45
164   RCLE    36 15
165     x       -35
166     1        01
167   X⇄Y       -41
168     -       -45
169   STOD    35 14
170   P⇄S     16-51
171   RCL3    36 03
172   RCLC    36 13
173     x       -35
174   STOC    35 13
175   LSTX    16-63
176   RCLD    36 14
177     x       -35
178   RCLI    36 46
179     x       -35
180   STOD    35 14
181   RCLA    36 11
182   RCL9    36 09
183     1        01
184     +       -55
185    Yˣ        31
186   RCL7    36 07
187     x       -35
188   RCL0    36 00
189     x       -35
190   P⇄S     16-51
191   RCL3    36 03
192     x       -35
193   RCL9    36 09
194     ÷       -24
195   RCLD    36 14
196     x       -35
197   1/X        52
198   STOD    35 14
199   RCLB    36 12
200     .       -62
201     8        08
202     0        00
203    Yˣ        31
204     .       -62
205     0        00
206     2        02
207     3        03
208     x       -35
209   RCL4    36 04
210     ÷       -24
211   RCL8    36 08
212     x       -35
213   P⇄S     16-51
214   RCL6    36 06
215     x       -35
216   RCLC    36 13
217     x       -35
218   1/X        52
219   RCLD    36 14
220     +       -55
221   1/X        52
222   PRTX      -14
223   P⇄S     16-51
224   RTN        24
```

*For Hewlett-Packard 67/97 Programmable Calculator

IV. OPERATION

First Run: Select a Value of RE_2 and store in register A. To begin the program, press key "A"

Subsequent Runs: [As necessary until the calculated and required value of NTU C_{min} agree] Select a value of RE_2 and store in register A. To begin the program press key "B".

HEAT EXCHANGER DESIGN PROBLEM

APPENDIX IV

A. Description

Appendix III procedure can be used for sizing crossflow finned tubular heat exchangers. The following data, taken from reference [2], is used to determine the required heat-exchanger size for the given conditions.

The design is that of an intercooler for a 5000 SHP gas turbine plant.

DESIGN CONSTRAINT	SIDE I	SIDE II
Surface	Smooth Tube	Finned Tube 11.32-.737 SR [Fig 106]
D_h	.01224 FT	.01152 FT
δ	N/A	.00033 FT
β	42.1 FT^2/FT^3	270 FT^2/FT^3
A_δ/A_T	N/A	.845
ℓ	N/A	.225 IN
W	400,000 LB/HR	200,667 LB/HR
T_{in}	60 ^{0}F	260 ^{0}F
T_{out}	82 ^{0}F	80 ^{0}F
ΔP	1.554 PSI	.306 PSI
μ	2.36 LB/HR-FT	.0482 LB/HR-FT
C_p	1.0 BTU/LB-^{0}F	.2436 BTU/LB-^{0}F
ρ_m	62.38 LB/FT^3	.1755 LB/FT^3

	SIDE I	SIDE II
P_R	6.8	.70
K_m	N/A	100 BTU/HR-FT-^{0}F
F	.55 IN	N/A
b	.79 IN	N/A
A_c	.0560 IN^2 (From Fig 106)	Calculate

B. Calculations

$$\beta_1 = {}^{A}c/A_{fr}[4/D_h] = \frac{[.0560\ IN^2]\qquad [4]}{[.55\ IN\ X\ .79\ IN]\ [.01224\ FT]}$$

$$= 42.1\ FT^2/FT^3 \tag{1}$$

$$\beta_2 = 270\ FT^2/FT^3 \tag{2}$$

$$K_1 = [42.1]\ [.01224/4] = .129 \tag{3}$$

$$K_2 = [270]\ [.01152/4] = .778 \tag{4}$$

$$K_3 = \frac{[400,000]\ [.778]}{[200,667]\ [.129]} = 12.038 \tag{9}$$

$$K_4 = \frac{[1.554]\ [.01224]\ [62.38]}{[.3061]\ [.01152]\ [.1755]} = 1917.8 \tag{11}$$

$$K_5 = \frac{[12.038]^2}{[1917.8]} = .0756 \qquad (13)$$

$$K_6 = \frac{[.0756]}{[12.038]^3} = 4.333 \text{ X } 10^{-5} \qquad (14)$$

CALCULATIONS FOR THE FINAL RE_2 SELECTED WILL BE SHOWN:

Select $RE_2 = 5760$

From the data of Surface 2 [Figure 106] read:

$f_2 = .021$ $\qquad$ $j_2 = .0054$

In order to be strictly consistant with the design presented in Ref [2], friction factor $[f_1]$ will be taken from Figure 29 of Ref [2], rather than employ any linear approximations suggested in the design procedure:

From Figure 29 data for surface 1 and Equation (16):

$RE_1 = 5073$ $\qquad$ $f_1 = .0072$

$$G_2 = \frac{RE_2\ \mu_2}{D_{2h}} = \frac{[5760]\ [.0482]}{[.01152]} = 24{,}100 \text{ LB/HR-FT}^2$$

$$X = \frac{[.306]\ [.01152]\ [144]\ [32.2]\ [3600]^2\ [.1755]}{[2]\ [0.021]\ [24{,}100]^2} \qquad (22)$$

$$X = 18.29 \text{ IN} \tag{22}$$

$$Y = 5.34 \text{ FT} \tag{23}$$

$$Z = \frac{[400{,}000]/978{,}127]}{[.129]\ [18.28/12]} = 2.08 \text{ FT} \tag{24}$$

$$\text{where } G_1 = \frac{[5073]\ [2.36]}{[.01224]} = 978{,}127 \text{ LB/HR-FT}^2$$

$$N = \frac{[18.29]\ [24.96]}{[0.55]\ [[0.79]} = 1051 \tag{25}$$

Once again, in order to be strictly consistant with the design presented in Ref [2], Colburn Modulus [j_1] will be taken from Figure 28 of Ref [2], rather than employ any linear approximations suggested in the design procedure:

From Figure 28 data for surface 1 @ $RE_1 = 5073$:

$j_1 = 0.00502$ (read $N_{st} = .0014$ and compute j]

$$h_1 = [0.005]\ [1.0]\ [978{,}127]\ [6.8]^{-.667}$$

$$= 1368 \text{ BTU/HR FT}^2\ {}^0\text{F} \tag{28}$$

$$h_2 = [0.0054]\ [.2436]\ [24{,}100]\ [0.700]^{-.667} \tag{29}$$

$$= 40.21 \text{ BTU/HR FT}^2\ {}^0\text{F}$$

$$m_2 = \sqrt{(2)\ (40.21)/\ (.00033)\ (100)}$$

$$= 49.3\ \text{FT}^{-1} \qquad (30)$$

$$\eta_{\delta\text{-L}} = \frac{\text{Tanh}\ [49.3]\ [.225/12]}{[49.3]\ [.225/12]} = 0.788 \qquad (30a)$$

$$\Delta\eta_{\text{correction}} = 0\ \text{[For consistancy with Ref (2) example]*} \qquad (31)$$

$$\eta_o = 1 - .845[1 - .788] = 0.82 \qquad (32)$$

$$\frac{1}{AU_{\text{calculated}}} = \frac{1}{[1368][711.55]} + \frac{1}{[40.21][0.82][4570.9]}$$

$$= \frac{1}{130{,}506\ \text{BTU/HR-}^0\text{F}} \qquad (33)$$

In order to complete the design procedure, compute AU_{required} and compare with equation (33) results:

$$[AU]_{\text{required}} = \text{NTU}\ C_{\text{min}}$$

$$C_{\text{min}} = C_{\text{air(side II)}} = [200{,}667]\ [.2436]$$

$$= 48{,}883\ \text{BTU/HR-}^0\text{F}$$

$$C_{\text{max}} = C_{\text{water(side I)}} = 400{,}000\ \text{BTU/HR-}^0\text{F}$$

$$\varepsilon = \frac{260 - 82}{260 - 60} = 0.89 \qquad (34b)$$

From Figure 5 of Reference [2], for a cross-flow exchanger with both fluids UNMIXED, and $C_{min}/C_{max} = 0.122$ with $\varepsilon = 0.89$, [or from Table 4 of Ref [2] with proper interpolation] the $NTU_{req'd}$ is found to be 2.67.

$$NTU_{req'd}C_{min} = [2.67][48,883] = 130,517 \text{ BTU/HR-}^0\text{F} \qquad (35)$$

Comparing Equation (33) with equation (35):

$$NTU_{req'd}C_{min} \overset{?}{=} NTU_{calculated}\ C_{min}$$

$$130,517 \text{ BTU/HR-}^0\text{F} = 130,506 \text{ BTU/HR-}^0\text{F}$$

CLOSE ENOUGH!

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* Surface 2 is a rectangular fin sheet and, to be strictly correct, a correction should be applied to permit the use of equation (30a) as outlined in the design procedure.[See Appendix III, Table I] In order that the results of this example will be consistant with those of reference [2], a correction of 0 will be assumed pursuant to the simplifying assumptions as stated in the example of reference [2].

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